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## Editors´ Preface

Civil and Building Engineering have long been application areas for computing and other information and communication technologies (ICT). These proceedings are from the 37th International Conference of the CIB W78 - Information Technology in Construction, a series started almost 40 years ago by this CIB Working Groupon IT in Construction. Along with the International Society on Computing in Civil and Building Engineering (ISCCBE), these are two of the most important international institutions dedicated to promote computing and information technologies in the construction sector and, in 2020, came together to promote **the 2020 ICCCBE + CIBW78 Virtual Joint Conference**.

Despite all research efforts, the construction industry until recently was reluctant to more fully adopt ICT on its processes. That status started swiftly to change with the widespread Building Information Modelling (BIM) adoption which spearheaded a cultural change on the sector, making some other related technologies worth attention in the eyes of this industry stakeholders.

So now we are at a very special moment when research in this important area can make a real difference, impacting productivity and quality of thousands of construction projects around the world, both in building and infrastructure projects, reducing or eliminating so common time and cost overruns.

The papers contained in this volume are representative of the ultimate research trends on this theme and are authored by some of the leading researchers in the world. Together, they provide an updated review of current scientific developments as well as practical applications of Computing and ICT in Civil and Building Engineering.

Some outstanding examples are the sections on Machine Learning, Blockchain and Vision-based applications, as well as on the recent trends of BIM uses in Infrastructure Projects and during the Construction Phase.

We hope this book will be useful and informative both to the academic community and to practitioners in the construction industry looking for high quality and updated research on Computing and ICT for Civil and Building Engineering.

**Eduardo Toledo Santos**
**Sergio Scheer**

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# DEEP NEURAL NETWORKS FOR DRONE VIEW LOCALIZATION AND MAPPING IN GPS-DENIED ENVIRONMENTS

**Yalong Pi[1], Nipun D. Nath[2], and Amir H. Behzadan[3]**

**Abstract:** Geolocation information used to create ground survey maps is critical in many domains including construction, transportation, urban planning, disaster response, agriculture, forestry, ecology, mining, and defence. Rapid development of the UAV technology due in part to better camera resolution, longer flight range, and higher data storage capacity, has enabled more efficient, less expensive remote sensing at lower altitudes. While UAV remote sensing requires uninterrupted access to on-board GPS data, such information may not be always available (e.g., in GPS-denied environments). Also, UAV pilots and enthusiasts may not share location information due to privacy issues or lack of knowledge about geolocation meta-data. Advances in vision-based deep learning have created new opportunities in UAV data collection and navigation beyond the constraints of GPS-enabled environments. In particular, UAVs equipped with RGB cameras can be deployed to automatically recognize and map target objects and landmarks on the ground using deep learning methods. This paper presents a method for real-time aerial data collection and GPS-free mapping. This is achieved by passing UAV visual data through a convolutional neural network (CNN) to identify and localize target objects, followed by applying geometric transformation to instantaneously project detected objects on an orthogonal map, all without GPS data. Particularly, the pixel coordinates of ground objects and four reference points are first detected by the CNN model. Next, viewpoint transformation is applied to project detected objects from the UAV's perspective view onto an orthogonal view. Experiments conducted in an outdoor field yield a small average error of <2% along X and Y axes.

**Keywords:** Convolutional Neural Network (CNN), GPS-Denied, Unmanned Aerial Vehicle (UAV).

## 1 INTRODUCTION

### 1.1 Object Mapping Using Geolocation Information

Geolocation information are widely used by mapping platforms (e.g., Google Maps, OpenStreetMap, ArcGIS) to overlay objects on maps, and are critical components of decision support and research infrastructure in many fields including agriculture, forestry, ecology, marine industry, mining, commerce, construction, transportation, defense, disaster response, and urban planning. Existing methods of mapping data collection can be divided into two broad categories of ground survey and aerial remote

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sensing. Ground survey methods involve using total stations and ground photogrammetry. A total station is used to measure the coordinates of ground control points (GCPs) to produce detailed vector maps, which can reach an accuracy of <1 millimeter. However, processing data using this method is time consuming, and the range of data collection is relatively limited. Ground photogrammetry, on the other hand, involves using optical cameras, sonar, radar, and laser scanners to collect digital spatial information. This method can produce 3D models providing that high-accuracy GCP information is available (Adams et al. 2011). In contrast to ground survey methods, aerial remote sensing includes collecting rasterized images from satellites, airplanes, and unmanned aerial vehicles (UAVs). More recently, GPS-enabled light detection and ranging (LIDAR) equipment has been also used from low-altitude aircrafts for this purpose (Carter et al. 2012).

Using satellite imagery for real-time applications at micro-urban level of detail may pose certain challenges. In addition to high cost of acquiring and processing large volumes of satellite data, accessing such data in some locations or during certain times may be restricted, data could be interrupted due to cloud blocking (Adams et al. 2011), and update rate could be too slow (e.g., once every 24 hours) (NASA 2020). Moreover, majority of existing remote sensing data analysis techniques rely on the availability of GPS data, which may hinder their applications in GPS-denied environments (locations and times where GPS signal is weak or non-existent) for timely status monitoring, decision-making, resource deployment, and emergency management. Examples include locations inside heavily urbanized areas or surrounded by dense vegetation, indoor facilities (e.g., tunnels, sheltered spaces, underground, underwater), GPS-jammed locations (i.e., presence of radio signal interference impacting GPS signal reliability), unknown territories (e.g., battlefield, extraterrestrial exploration), or during severe weather.

In the past decade, rapid development of the UAV technology due in part to better camera resolution, longer flight range, and higher data storage capacity, has enabled more efficient, less expensive remote sensing methods at lower altitudes (Adams et al. 2011). Despite their affordability and ease of use, UAV remote sensing is still not a trivial task since it requires uninterrupted access to on-board GPS data to calculate location information and generate ground survey maps. However, in some cases, such information may not be readily available (e.g., in GPS-denied environments), and sometimes, UAV pilots and enthusiasts may not share location information due to privacy issues or the lack of knowledge about how to create and exchange geolocation meta-data. In light of these limitations, advances in computer vision (CV) and machine learning (ML) have created new opportunities for pushing the boundaries of UAV data collection and navigation beyond the constraints of GPS-enabled environments.

In particular, UAVs equipped with standard RGB cameras can be deployed to automatically recognize landmarks (both manmade and natural) and targets of interest (ToIs) on the ground using deep learning methods such as convolutional neural networks (CNNs) (Adams 2011). This research aims at developing a method for GPS-free aerial data collection and mapping in real-time. This is achieved by passing the collected visual data through a CNN architecture, namely, RetinaNet (Lin et al. 2017) to identify and localize ToIs in each video frame, followed by applying geometric transformation to instantaneously project detected ToIs on an orthogonal map, all without involving GPS data. In this paper, current research progress on the relevant topics, as well as two approaches for collecting, analyzing, and mapping UAV visual data using ground reference points are introduced and validated in real-world experiments. Potential applications of the proposed methods are also discussed.

## 1.2 Previous Work

CNNs have been used in recent years for image classification, recognition, and semantic segmentation (i.e., extracting semantic information from images). For example, Krizhevsky et al. (2017) proposed AlexNet, a CNN with 8 layers, which accomplished top-5 error of 15.3% on ImageNet dataset. Later, Simonyan and Zisserman (2016) introduced VGGNet with up to 19 layers and achieved higher accuracy. He et al. (2017) designed a network with residual blocks, namely ResNet, that outperformed human by 3.57% on ImageNet.

Object detection further expands upon object classification by localizing the pixel-level position of target classes in the image. Examples of state-of-the art algorithms for object detection include R-CNN (Girshick 2014) and Fast R-CNN (Girshick et al. 2015) that use region of interest (RoI) to improve prediction speed compared to the traditional sliding box methods. To further reduce the processing time, Ren et al. (2017) proposed Faster R-CNN by adopting region proposal network (RPN) that achieved mean average precision (mAP) of 73.2% on PASCAL dataset (Russakovsky et al. 2015) (containing everyday objects such as people and cars). These methods involve two stages, i.e., proposing candidate regions and classifying proposed regions, and can produce significantly accurate predictions. There are also one-stage detectors that are specifically designed to compute faster, but with smaller accuracy loss (Lin et al. 2017). For example, Redmon et al. (2018) introduced You-Only-Look-Once (YOLO) version 3, which is the latest version of YOLO (Redmon et al. 2016) and YOLO version 2 (Redmon et al. 2017) algorithms. In particular, YOLO adopts feature pyramid network (FPN) and anchor boxes in the gridded image to predict class and location simultaneously. Liu et al. (2016) introduced single shot detector (SSD) using pre-defined boxes and scaled feature maps, and achieved 76.8% mAP on the VOC dataset (Everingham et al. 2010). Recently, Lin et al. (2017) presented RetinaNet with a novel focal loss integrated with FPN to better learn hard examples, resulting in 37.8% average precision (AP) on the COCO dataset (Lin et al. 2014).

While the field of CV, and in particular, CNNs for object detection and segmentation is rapidly developing, few studies have focused on aerial object recognition using CNNs. For example, Han et al. (2014) proposed a new weakly supervised algorithm that achieved an overall 94.45% precision on Google Earth, and Landsat (dataset containing airplanes, vehicles, and airports). Cheng et al. (2016) introduced rotation-invariant CNN with a new objective function via enforcing training samples before and after rotating, resulting in 72.63% precision on the VHR dataset. Tang et al. (2014) used extreme learning machine (ELM) and deep neural network (DNN) to classify if satellite images contain boats, and reached 97.58% accuracy. However, these methods detect only pixel coordinates of objects in satellite images without providing any geographic coordinates.

In the field of UAV-based remote sensing, researches have mostly focused on photogrammetry and 3D mapping. For example, Friedel et al. (2018) showed the possibility of mapping landscape soils and vegetation through self-organizing map (SOM) of the aerial spectral information. Chao et al. (2012) demonstrated the use of monocular cameras to build visual simultaneous localization and mapping (SLAM) tools to navigate a UAV without GPS. Suh and Choi (2017) explored using GCPs and UAVs to produce maps with 14-cm error in a mining site. Ventuna et al. (2016) investigated 3D modeling of coastal fish nursery environment with drone cameras and GCPs with high accuracy

(89.1%). Cunliffe et al. (2016) used UAV-captured photos and structure-from-motion (SfM) to produce accurate grain biophysical data. While these approaches can produce local 3D maps of the topography and space, to obtain target information (quantity, coordination, and status), post-processing (e.g., map stitching and target marking) and GPS data are still needed. It is evident that in GPS-jammed sites (i.e., military sites or enemy territories), GPS-based mapping methods fail to provide instantaneous position, velocity, and time (PVT) information (Asher et al. 2011).

Some researchers have tried to leverage other onboard sensors such as inertial measurement unit (IMU), stereo cameras, Wi-Fi, radio-frequency identification (RFID) (Balamurugan et al. 2016), and sonar to extract PVT information in GPS-denied environments. For example, Pestana et al. (2013) utilized OpenTLD tracker to follow moving objects such as humans and cars with UAV cameras without GPS. Rajeev et al. (2019) investigated the use of prior knowledge and augmented reality (AR) to navigate in indoor GPS-denied areas. Bachrach et al. (2012) equipped drones with RGB-D cameras to automatically plan complex 3D paths. Scaramuzza et al. (2014) designed a visual–inertial multi UAV system with camera and IMU to autonomously fly and map the environment. While previous work has investigated sensor data fusion for GPS-denied UAV navigation, the problem of single monocular RGB camera-based UAV navigation using ToI recognition (locating, projection, counting) and mapping still remains unexplored. As previously discussed, the ability to locate and map objects using ordinary RGB cameras mounted on lightweight UAVs could be of significant value in many applications, and reduce the cost of data collection. Therefore, this research is geared toward the introduction and validation of a robust, computationally efficient method for identifying, locating, and mapping ToIs from UAV cameras in GPS-denied environments.

## 2 METHODOLOGY

### 2.1 Transformation of Pixel Coordinates to Real-World Positions

In this research, the process of mapping UAV-captured scenes is carried out in two phases: (i) identifying ToIs in aerial views and locating them within the image (perspective) coordinate system (a.k.a., pixel coordinates), followed by (ii) projecting ToI positions to the real-world (orthogonal) coordinate system (a.k.a., real-world positions). To obtain the real-world orthogonal position of a point from its perspective pixel coordinates, four reference points (where any three points are non-collinear) with known pixel coordinates and corresponding real-world positions are needed.

Figure. 1 shows an example, where pixel coordinates of the reference points are $(x_1, y_1)$, $(x_2, y_2)$, $(x_3, y_3)$, and $(x_4, y_4)$, and corresponding real-world position are $(x'_1, y'_1)$, $(x'_2, y'_2)$, $(x'_3, y'_3)$, and $(x'_4, y'_4)$, respectively. Given $M$, the real-world position $(x'_5, y'_5)$ of any point (i.e., ground ToI) can be calculated from its pixel coordinates $(x_5, y_5)$ using Equations 6 and 7. In Equation 6, $(x''_5, y''_5, w)$ represents the point's position in a homogenous coordinate system where $1/w$ is the distance of the point from camera (i.e., $w = 0$ represents that point is at infinite distance).

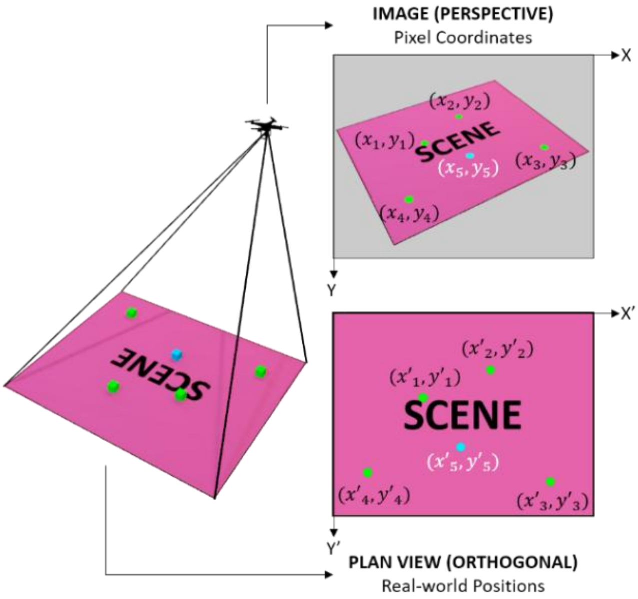


Figure 1. Perspective to orthogonal transformation.

$$\begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ 1 & 1 & 1 \end{bmatrix} . \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} x_4 \\ y_4 \\ 1 \end{bmatrix} \#(1)$$

$$A = \begin{bmatrix} a_1.x_1 & a_2.x_2 & a_3.x_3 \\ a_1.y_1 & a_2.y_2 & a_3.y_3 \\ a_1 & a_2 & a_3 \end{bmatrix} \#(2)$$

$$\begin{bmatrix} x'_1 & x'_2 & x'_3 \\ y'_1 & y'_2 & y'_3 \\ 1 & 1 & 1 \end{bmatrix} . \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} x'_4 \\ y'_4 \\ 1 \end{bmatrix} \#(3)$$

$$B = \begin{bmatrix} b_1.x'_1 & b_2.x'_2 & b_3.x'_3 \\ b_1.y'_1 & b_2.y'_2 & b_3.y'_3 \\ b_1 & b_2 & b_3 \end{bmatrix} \#(4)$$

$$M = B.A^{-1} \#(5)$$

$$\begin{bmatrix} x''_5 \\ y''_5 \\ w \end{bmatrix} = M. \begin{bmatrix} x_5 \\ y_5 \\ 1 \end{bmatrix} \#(6)$$

$$x'_5 = \frac{x''_5}{w}, y'_5 = \frac{y''_5}{w} \#(7)$$

## 2.2 Object Detection Framework

CNN models, trained on relevant datasets, can effectively detect objects based on visual features and output the pixel coordinates of detected objects. With proper training data, UAVs equipped with cameras can also detect objects on the ground (e.g., parking lots, people, landmarks, trees, buildings) from the perspective view. These objects can serve as reference points (Figure 1). The pixel coordinates of any ToI is also produced by the same CNN model. However, there is a trade-off between speed and accuracy of different CNN architectures, as shown in Table 1. In this research, the goal is to process images in real-time with high accuracy. Therefore, RetinaNet-50-500 (4) is selected since its focal loss function emphasizes on learning hard examples, leading to high accuracy without compromising real-time speed.

Table 1. Average precision (AP) vs. time on COCO test-dev dataset.

| CNN model | AP (%) | Time (milliseconds) |
|---|---|---|
| YOLOv2 (Redmon et al. 2016) | 21.6 | 25 |
| SSD321 (Liu et al. 2016) | 28.0 | 61 |
| R-FCN (Dai et al. 2016) | 29.9 | 85 |
| RetinaNet-50-500 (Lin et al. 2017) | 32.5 | 73 |
| DSSD513 (Liu et al. 2016) | 33.2 | 156 |
| FRCN (Dai et al. 2016) | 36.2 | 172 |
| RetinaNet-101-800 (Lin et al. 2017) | 37.8 | 198 |

## 2.3 Viewpoint Transformation

Once the CNN model identifies the pixel coordinates of the reference points and ToIs, the next step is to obtain each ToI's real-world position given the real-world positions of the reference points. The real-world positions of the reference points can be obtained either from prior-knowledge (e.g., using on-site measurements) or from a plan-view image (using the ratio between detected size of an object and its known actual physical size). In this Section, the problem of calculating the real-world position and orthogonal mapping of ToIs is approached from two angles: (i) projection from perspective to orthogonal based on reference objects' coordinates (PROC), and (ii) projection from perspective to orthogonal based on reference objects' size (PROS).

Figure 2 illustrates the workflows of PROC and PROS approaches. In this Figure, four traffic cones are used as reference objects, and the goal is to calculate the orthogonal position of a moving person (i.e., ToI) from UAV-captured perspective views. In the PROC approach, first, Model-P is trained on a perspective video (PV1) and tested on another perspective video (PV2) to predict the pixel coordinates of the reference objects and ToI in each video frame. Next, from the known real-world positions of the reference objects, the real-world position of the ToI (i.e., $x'_5, y'_5$) is calculated in PV2 using Equations 1 through 7. While the PROC approach relies on the real-world positions of reference objects, the PROS approach uses the size of reference objects. The pixel coordinates of reference objects and ToI are obtained as before by using Model-P. However, the reference objects' real-world positions are calculated differently. In essence, another CNN model, Model-O, is trained on an orthogonal video (OV1) and tested on another orthogonal video (OV2) to predict the boxes of the reference objects. Since in the PROS approach, the actual sizes of reference objects are known, the ratio between the sizes of the predicted boxes in pixel and their real sizes is used to transform the pixel coordinates of these objects to real-world positions. Next, the real-world position of the ToI is calculated in PV2 using Equations 1 through 7.

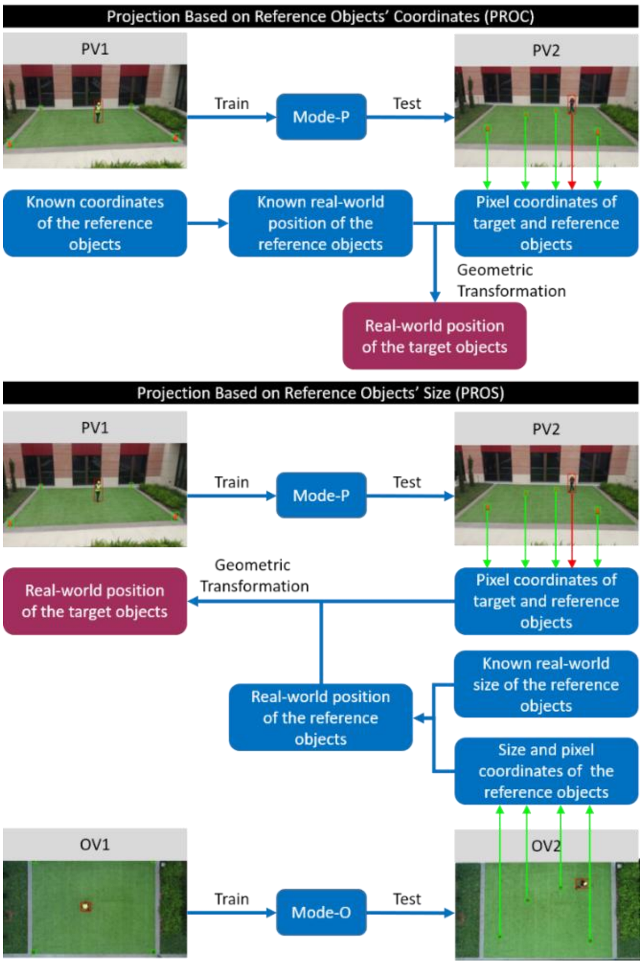


Figure 2. Reference objects in perspective and orthogonal views are used to calculate the real-world position of a walking person.

## 3 APPLICATIONS

The large volume of available geocoded data (e.g., 3D building models with geographic information) and crowd-sourced video data, especially in urban areas, enables the training of CNN models to effectively recognize natural and manmade landmarks as ground reference objects. In some cases, where a sufficient number of references objects does not exist, manually placed markers (e.g., GCPs) can be also used. Nonetheless, with CNN models capable of recognizing multiple reference objects in perspective views and given information about the real-world positions of these objects, the PROC approach can be used to map multiple ToIs (both stationary and moving) in real-time.

In some scenarios, however, it might not be possible to obtain accurate real-world positions of the reference objects beforehand. In these cases, knowing the physical size of the reference objects, the PROS approach can be used to produce orthogonal maps of

ToIs. This approach requires (at least) one orthogonal image (e.g., from a second UAV camera, an airplane, or a passing satellite looking down vertically) to calculate the real-world positions of the reference objects. The PROS approach is therefore more generalizable compared to the PROC approach since most of the prior knowledge in PROS can be obtained beforehand or with little dependency on the actual site. Table 2 is a summary of potential applications of both approaches. Examples listed in this Table can be implemented using the PROC approach if there are adequate reference objects (4 or more). Examples marked with (*) indicate that the PROS approach is more suitable due to the potential of insufficient data about reference object positions (e.g., moving reference objects).

Table 2. Potential applications of PROC and PROS mapping methods.

| Domain | Reference Points (Landmarks) | Potential TOIs | Application |
|---|---|---|---|
| Disaster management | Parking lot, intersection, building | People, car, debris, damaged roof | Search and rescue, damage estimate |
| Agriculture* | Tractor, building, road post | Livestock, crops, grass, vegetation | Growth estimate, fleet control |
| Forestry* | Cliff, river, equipment | Trees, animals | Fire control, animal migration |
| Marine systems* | Lighthouse, pier, building, vessels | Marine animals, corals, vessels, oil spill | Navigation, marine ecology |
| Construction management | Building element (wall, column), equipment | Material stocks, workers, equipment | Safety, work monitoring, productivity estimate |
| Transport systems | Road sign, toll plaza, control tower | Cars, trucks, trailers, planes | Traffic monitoring and control |
| Urban management | Parking lot, intersection, building | Buildings, trees, people | Urban planning, land survey |
| Military defence* | Military post, tent, installation | Adversary | Surveillance, target inspection |

# 4 EXPERIMENTS

To train and test CNN models that can automatically detect reference objects and ToIs, two experiments are conducted. Experiment 1 involves collecting perspective video PV1 (Figure 3) and orthogonal video OV1 (Figure 4), which provide the training data for the perspective model (Model-P) and orthogonal model (Model-O). Experiment 2 contains two videos, PV2 (Figure 5) and OV2 (Figure 6), that serve as testing data.

## 4.1 Data Collection and Description

The objective of both experiments is to project a moving ToI captured in UAV's perspective view into real-world (orthogonal) coordinates, using four reference points. Therefore, each experiment contains a continuously moving person (ToI) and four traffic cones (reference objects). The cones and the person are located on a turf (333 in × 426 in).

To obtain ground-truth information, one drone (Parrot Anafi) records the scene from an aerial angle pointing the camera vertically downward (videos OV1 and OV2). Another drone (Parrot Bebop 2) records the same scene from a perspective angle and an arbitrary altitude (videos PV1 and PV2). The cones' positions in Experiment 1 (PV1 and OV1) are different from Experiment 2 (PV2 and OV2). Also, the person changes outfit between the two experiments. With the upper left corner of the turf designated as the origin of the real-world coordinate system, the real-world positions of the four cones are shown in Figure 3 through 6. For example, cones in Experiment 1 are placed at coordinates (0, 0), (0, 333), (426, 0), and (426, 333), whereas in Experiment 2, they are placed at coordinates (56, 263), (148, 138), (258, 95), and (356, 277). The timestamps of PV2 and OV2 videos are carefully synchronized, leaving a total of 4,149 frames for projection. To train and test the CNN models for detection of cones and person, all collected videos are manually annotated with DarkLabel (DarkLabel 2020), frame by frame, as shown in Figure 3 through 6.

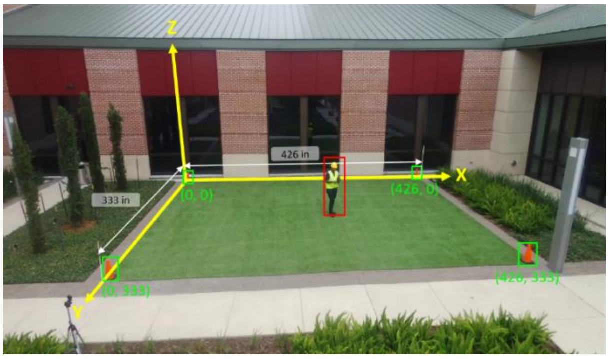


Figure 3. Perspective video 1 (PV1) annotation sample and setup.

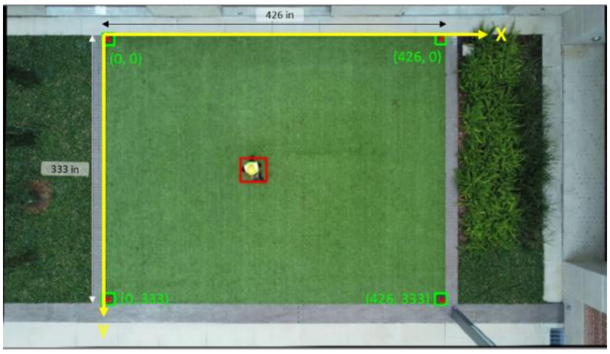


Figure 4. Orthogonal video 1 (OV1) annotation sample and setup.

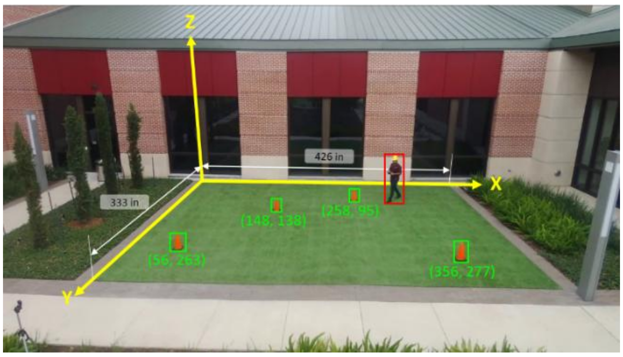


Figure 5. Perspective video 2 (PV2) annotation sample and setup.

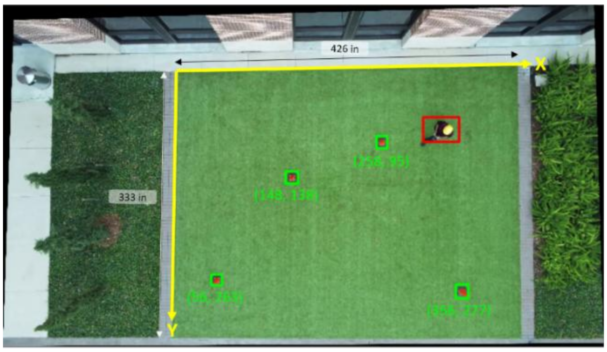


Figure 6. Orthogonal video 2 (OV2) annotation sample and setup.

In these Figures, green rectangles represent cones, and red rectangle represents person. Description of the experimental data is shown in Table 3. The ground-truth real-world positions of the person are retrieved from the manually annotated OV2 video. All frames within PV1 and OV1 are used for training while the frames in PV2 and OV2 are used for testing. For the training of Model-P and Model-O, the learning rate is set to 10-4 and batch size is set as 4.

Table 3. Data statistics for experiments 1 and 2.

| | Experiment 1 | | Experiment 2 | |
|---|---|---|---|---|
| | PV1 | OV1 | PV2 | OV2 |
| Total frames | 8,873 | 9,915 | 5,261 | 5,814 |
| Person instances | 8,813 | 8,223 | 4,492 | 4,773 |
| Cone instances | 33,362 | 32,892 | 19,650 | 19,092 |

## 4.2 Projection Based on Reference Objects' Coordinates (PROC)

Model-P is responsible for detecting the pixel coordinates of cones and person in PV2. Figure 7 shows an example of detection of cones (yellow boxes) and person (white box). All detected boxes are associated with a confidence level predicted by the model. The four cones and one person that are detected with the highest confidence levels are selected for further analyses.

Next, pixel coordinates, i.e., the center point of the bottom edge of each detection box (marked with dots in Figure 7) are determined as input for projection calculation. From the calculated pixel coordinates of four cones and their corresponding real-world positions, the person's real-world position is calculated (using Equations 1 through 7), and projected on the orthogonal map shown in Figure 8. Also, the annotated person's position in OV2 is projected on the same coordinate system which serve as ground-truth. As expected, there may be situations when the PROC approach fails to project, e.g., when Model-P cannot detect at least four cones in the frame, because they are either not within the camera view or obstructed by other objects. In this work, such frames are removed from analysis. The number of skipped frames, presented as the percentage of total number of frames, is termed frame loss (Equation 8) which describes how efficiently the model utilizes the input video data. Moreover, due to the noise in data and/or detection error, sometimes the detected boxes of the same object (e.g., cone) in two consecutive video frames could appear in two considerably different locations. To identify such statistical outliers, X- and Y- coordinates of each objects are treated as a timeseries data. Given, a timeseries data of the coordinates of an object, $C = \{c_t; t = 1,2,\ldots,n\}$, at frame $t = n$, we consider 15 previous consecutive data points, $C' = \{c_t, c_{t-1}, \ldots, c_{t-14}\}$, and calculate its mean $c'_{mean}$ and standard deviation $c'_{STD}$. If the current reading $c_t$ is a statistical anomaly, defined as $c_t - c'_{mean} \geq k * c'_{STD}$ (two cases with $k$ = 2 and 3) we consider the detection as an outlier. After removing the outlier predictions, the average projection error is recalculated.

$$frame\ loss\ (FL)\ \% = \frac{\#\ of\ skipped\ frames}{total\ \#\ of\ frames} * 100\#(8)$$

Figure 7. Example of detections of person and cones.

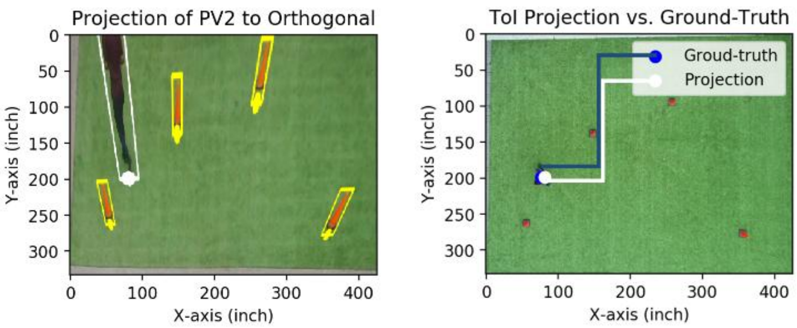


Figure 8. Perspective to orthogonal projection.

## 4.3 Projection Based on Reference Objects' Size (PROS)

As described earlier, the difference between PROC and PROS approaches is in the method for acquiring the reference objects' real-world positions. In the PROS approach, it is assumed that the size of an object in pixel units in the orthogonal image will represent a constant physical size throughout the entire video. Based on this assumption, from the known physical size of the target object, its actual position (in inches) can be calculated solely based on the model's predictions in the orthogonal view. In the experiments conducted, the actual dimensions of the traffic cone are known to be 10 inches (both length and width). However, due to the noise in data and/or human error, the annotated training boxes are slightly bigger than the actual size of the cones. From the training data (OV1), the width of the detection boxes for cones is calculated to be 14.56 inches on average. Therefore, it is assumed that the detected boxes for the same cones in the test data (OV2) would also have the same average physical size. During the test, Model-O is applied to the first 30 frames (i.e., 1 second) of OV2 to obtain the sizes and coordinates of the boxes representing cones in pixel units. Next, knowing that the size of the boxes are 14.56 inches in real-world, coordinates are scaled accordingly to obtain the real-world positions of the boxes. The latter part (orthogonal projection) of the PROS approach is similar to the previously described PROC approach (Section 4.2).

# 5 RESULTS

## 5.1 RetinaNet Model Testing

Model-P and Model-O are tested on PV2 and OV2 to evaluate their performance, as shown in Table 4. Overall, Model-O produces 51% mAP which is worse than 97% for Model-P. One reason for this disparity is that from orthogonal view (in Model-O), the person and cones appear less distinctive compared to perspective view (in Model-P). For individual classes, Model-P detects class person with 99.21% average precision (AP); however, Model-O produces only 45.89% AP. Similarly, for class cone, Model-P produces 96.11% detection AP, compared to 51.97% AP for Model-O.

Table 4. Comparison of Model-P and Model-O performance.

| Model | mAP | AP (Cone) | AP (Person) |
|---|---|---|---|
| P | 97.66% | 96.11% | 99.21% |
| O | 48.93% | 51.97% | 45.89% |

## 5.2 Projection Results

Projection results obtained from PROC and PROS approaches are summarized in Table 5, and illustrated in Figure 9. For both PROC and PROS, the remaining frames after removing non-projectable frames (because the Model-P detected less than four cones or one person while tested on PV2) is 3,735 with 9.98% frame loss for both projections. The Euclidian distance (in inches) between the person's real-world and projected positions is reported as projection error in each frame. The average projection error (APE) is calculated as the mean of frame-by-frame errors in all projectable frames. As shown in Table 5, the PROS approach achieves an APE value of 15.39 inches, which is slightly better than PROC's APE of 17.18 inches. Next, the projected person's real-world X- and Y- coordinates are compared with the corresponding ground-truth coordinates, frame by frame, and the errors are divided by the total length along each axis (i.e., 426 inches for X-axis and 333 inches for Y-axis) to present the error as a percentage. The errors in PROC approach are 9.52 inch (2.23%) along X-axis and 11.79 (3.54%) along Y-axis, which is slightly outperformed by PROS approach with errors of 8.62 inches (2.02%) along X-axis and 10.41 inches (3.12%) along Y-axis.

Furthermore, two scenarios are considered for removing the outliers: k = 2 and k = 3 (Section 4.2). For k = 3, after removing outliers, a total of 1,493 (FL = 64.02%) and 1,488 (FL = 64.14%) frames remain in PROC and PROS, respectively, and the overall APE is improved to 13.86 inches (for PROC) and 11.86 inches (for PROS). When removing outliers with k = 2, calculated APEs (overall, X-, and Y-) for both approaches are greater than the case of k = 3, but smaller FL (26.63% for PROC and 26.71% for PROS) is achieved. Errors along X- and Y-axis for individual frames are documented in Figure 9. In general, it is observed that removing outliers leads to higher frame loss but smaller

APE in both approaches. Nonetheless, for all cases, the average error along any dimension is less than 4% which indicates the robustness of the proposed methods.

Table 5. Test results of PROC and PROS mapping methods.

| | Method | Direct Projection | Outlier (k = 2) | Outlier (k = 3) |
|---|---|---|---|---|
| Remained Frame # (FL %) | PROC | 3,735 (9.98%) | 3,044 (26.63%) | 1,493 (64.02%) |
| | PROS | 3,735 (9.98%) | 3,041 (26.71%) | 1,488 (64.14%) |
| Overall APE (inch) | PROC | 17.18 | 14.35 | 13.86 |
| | PROS | 15.39 | 12.31 | 11.85 |
| X-axis APE (inch and %) | PROC | 9.52 (2.23%) | 7.11 (1.66%) | 6.53 (1.53%) |
| | PROS | 8.62 (2.02%) | 5.89 (1.38%) | 5.37 (1.26%) |
| Y-axis APE (inch and %) | PROC | 11.79 (3.54%) | 10.89 (3.27%) | 10.87 (3.26%) |
| | PROS | 10.41 (3.12%) | 9.55 (2.86%) | 9.50 (2.85%) |

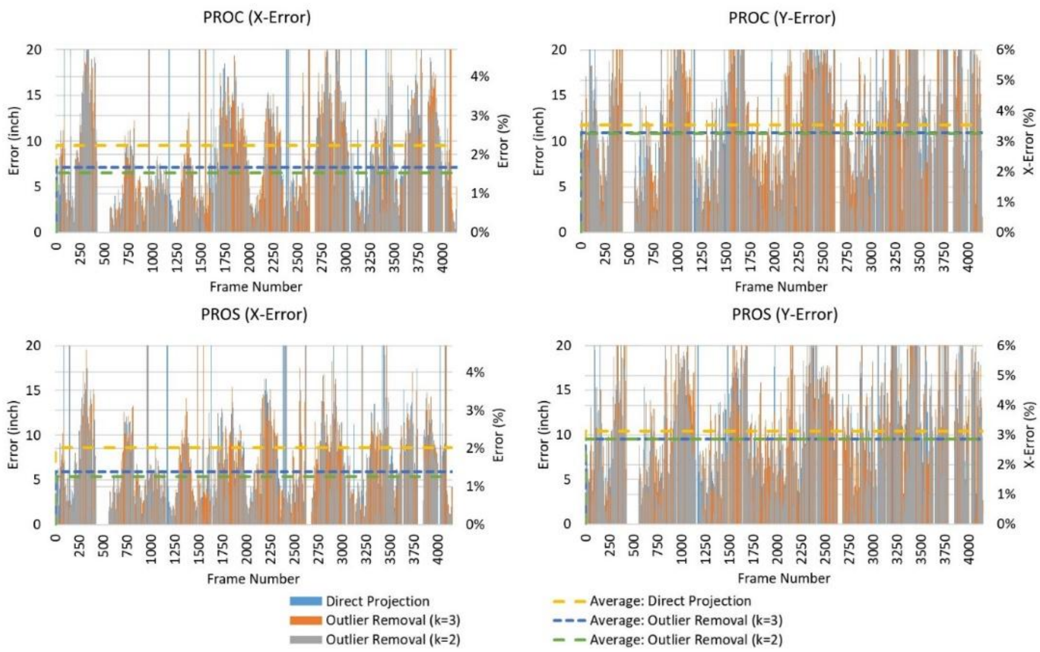


Figure 9. Frame-by-frame projection error in X- and Y- axes for PROC and PROS methods.

## 6 Conclusion

The research presented in this paper was motivated by the need for robust object detection and mapping from UAV-captured scenes in GPS-denied environments. By proposing a vision-based UAV localization and mapping framework, this work provided an alternative for GPS-denied target projection based on reference objects' coordinates or sizes. In addition, potential applications of GPS-denied UAV mapping in various domains were discussed. Separate experiments were conducted to produce training dataset (PV1 and OV2) and testing dataset (PV2 and OV2) for CNN models, and two mapping (perspective to orthogonal projection) approaches (namely PROC and PROS) were designed and validated. The PROC approach used the real-world coordinates of four reference points (e.g., natural or manmade objects on the ground) to project ToIs onto an orthogonal map. The PROS approach, on the other hand, was based on information about the physical size of reference objects (e.g., cars, land parcels, buildings). Based on this distinction, the PROS approach is deemed more suitable in scenarios with limited prior knowledge. Both approaches achieved APEs as small as 11.85 inches (PROS) and 13.86 inches (PROC) (1.26% and 2.85% along X- and Y- axes in PROS, compared to 1.53% and 3.26% along X- and Y- axes in PROC) which makes them a feasible solution for real-time localization and mapping of ToIs solely from RGB camera's inputs.

The presented work poses some limitations. For example, the designed methods utilize video input from only one UAV for detection and mapping, and work best under adequate illumination (RGB camera provides little information in dark or not well-lit scenes). Also, while both mapping methods require reference objects on the ground, such objects may not be readily available in some circumstances such as UAV missions in unknown territories or remote locations. Future research will investigate solutions to these and other problems including the possibility of using other visual bandwidths (e.g., thermal imagery) as well as creating ad-hoc reference points using multiple cooperative UAVs.

## 7 Acknowledgments

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# AUTOMATIC GENERATION OF ARCHITECTURAL LAYOUTS USING GENETIC ALGORITHMS IN BIM

Garbo Zhu[1] and J.J. McArthur [2]

**Abstract:** Room layout is a complex problem for architects, who must consider adjacencies, room sizes, site constraints, and circulation requirements. This research applies genetic and stimulated annealing algorithms to optimize space layout in two dimensions. Visual Programming Languages interfacing with BIM software are used to allow semantic and topological qualities of each room to be imported to develop complete floorplans. A series of case studies adopting different machine learning techniques are presented to demonstrate the relative performance of each approach, using the minimization of unusable space as a performance metric. Previous research has considered purely mathematical solutions to support the automation of these layouts, often resulting in irregular polygons or circular rooms; from an architectural standpoint, this is undesirable and thus a rectangle-packing algorithm has been developed and used. Future research to facilitate the adoption of this approach in architectural practice, particularly for large and complex buildings, is discussed.

**Keywords:** BIM, automatic floorplan generation, parametric model, genetic algorithms.

## 1 Introduction

Space planning is one of the most crucial segments in construction projects, as it directly affects the experiential quality, energy efficiency, and feasibility of the building. The process is often time-consuming and labor-intensive since it re-quires logical senses and previous work experience of the architects involved. However, with the rise of automated design technologies, repetitive tasks such as floor layouts, can now be assigned to computer, leaving creative works to designers. This research focuses on the preliminary phase of a construction project - room planning, intending to generate spatial relationship diagrams as the guidance for future architectural design. In this exercise, the demonstration will be adopting the typology of a small-scaled shopping mall and following the representational programs that are needed. This paper extends upon previous work of this type by eliminating the irregular room shapes developed by approaches such as circle packing and Voronoi, presenting instead a rectangle-packing algorithm developed to optimize floorplans. Further, to permit its application in practice, a BIM integration script is presented to create 3D rooms and map semantic data, resulting in true architectural floorplans.

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## 2 LITERATURE REVIEW

With developed technologies, the process of space planning has transformed into a multi-objective optimization problem to not only satisfy the design constraints but also achieve an optimal spatial configuration. There have been numerous studies conducted on the topic of room placement using different mathematical formulas and algorithms, for example (e.g., Merrell et al. 2010; Wong and Chan 2009; Nagy et al. 2017). Recently, parametric approaches have leveraged Genetic Algorithms (GA) (e.g., Rebaudengo and Reorda 1996), Simulated Annealing (SA) (e.g., Yi et al. 2014), and fixed grid/matrix layout (e.g., Sharafi et al. 2017). These have been used with optimization rules for minimum travel distances between room centroids (e.g., Liggett 2000), minimum dead spaces and overlaps (e.g., Baušys and Pankrašovaite 2005), or optimized energy use (e.g., Du et al. 2018).

Two algorithms of interest to this paper are GA and SA. GA (e.g., Tate and Smith 1995; Whitney 1994) is de-signed to speed up the solution-finding process to search for high-quality results under a confined framework. SA techniques (e.g., Van Laarhoven and Aarts 1987) help to eliminate and improve the common hill climbing problems faced by GA. Instead of being a population-based algorithm, SA uses an iterative single solution-based method, making it an exploitative algorithm. In standard result-mining algorithms, the new solution is accepted only if it meets the improved minimum value set by the selection mechanism. In SA, the indicator for an acceptable result can be based on a probability percentage, providing solutions that are more meticulous and closer to the global optima (e.g., Liggett 2000), and its use is recommended at the beginning of the search process (e.g., Liggett 2000; Szykman and Cagan 1997)

A current gap in the literature is the lack of linkage between theories and architectural applications. Most of the researches conducted have only been implemented based on randomized room dimensions within arbitrary boundaries. To accurately examine and improve the usability of space planning optimization techniques, a controlled scenario with defined space programming information is adopted.

## 3 METHODOLOGY

A case study approach was used to explore room layout options using a six-step process. First, a set of 17 rooms and the sample site of 35m x 35m (1225m$^2$) are established, along with the required adjacency relationships. Next, a circle packing algorithm is introduced to place all rooms on site. Thirdly, the result generated is optimized through machine learning techniques, including Genetic Algorithms and Simulated Annealing. Then, the optimized output is transformed into realistic square geometries, following the original spatial requirements. To eliminate overlapping boundaries, room outlines are shifted to accommodate the appropriate dimensions. The final step is to define polygons as data points to be input into BIM through Dynamo for Revit.

### 3.1 Room Datasheet

The proposed workflow starts with a spreadsheet (Table 1) containing spatial requirements and adjacency relationships between rooms as the input. There are three levels of spatial relationships between rooms: 1) adjacency, defining the requirement for rooms to be next to one another; 2) proximity, indicating a preference for rooms to be near one another, and 3) non-adjacency, indicating that rooms cannot share a common wall. To ensure interactivity and flexibility of the result, all information is linked back to the spreadsheet in real time which minimizes lag time and errors caused by delays.

Table 1: Room Datasheet Sample (truncated)

| Room ID | Room Name | Area | Radius | Diameter | ADJ | Proximity | Non-ADJ |
|---|---|---|---|---|---|---|---|
| R0 | Entrance | 25 | 2.82 | 5.64 | NA | NA | NA |
| R1 | Service Room | 30 | 3.09 | 6.18 | R16 | R6 | R9 |
| R2 | Electrical Room | 30 | 3.09 | 6.18 | R16 | R1 | R8 |

## 3.2 Room Planning Sequence

From the structured table, the data is then processed through a series of functions (Fig. 1), coded using Python 3.6. The order within the list is determined by the number of adjacent rooms those rooms acquired, arranged in descending order. All adjacency relationships are captured in an ordered dictionary, with the key being rooms that were placed last, and the values representing rooms that should be placed next.

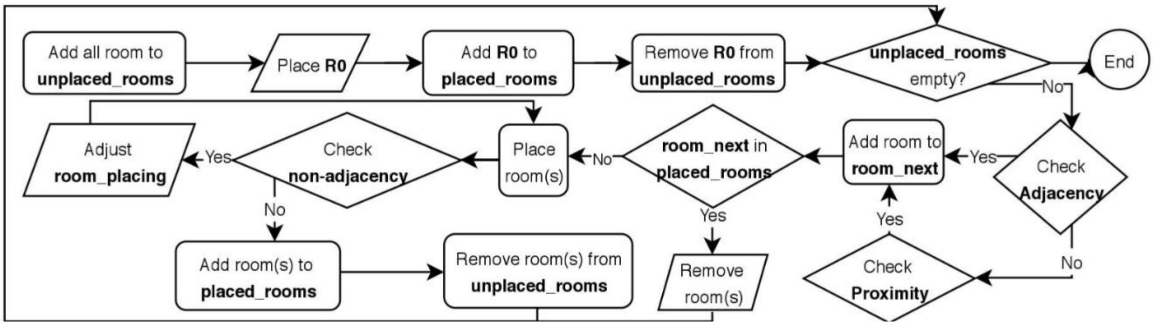


Fig. 1. Room Plotting Order Sequence

## 3.3 Room Placing Function – Circle Packing Algorithm

Circles are chosen as the primary visual representation due to their flexible quality with unlimited edges, giving more potential for spatial layouts. Stemming from the theory and logic behind circle packing algorithms (e.g., Collins and Stephenson 2003; Castillo et al. 2008), the proposed function introduced room planning sequence that governs the order and constraints of circle-plotting. Naturally, there will be dead spaces in-between each circle due to the curved outlines. Therefore, the input dimensions are smaller by 10% of the actual footprint required. Rooms are separated into three types of arrays for simple identification: array N, rooms that are currently being placed; array P, rooms that were placed prior to N; array D, rooms that are in the placed_rooms list. As each room ($N_i$) is added to the diagram, there are two rules that the function needs to satisfy. First, $N_i$ cannot exceed the site constraints (**Eq. 1-4**). Where x/y superscript denote the x/y - coordinate of the centroid, r superscript denotes the radius of the room, and $i$ subscript denotes the $i^{\text{th}}$ item in the array (Fig. 2).

$$N_i^x - N_i^r > \emptyset\ ;\ N_i^x + N_i^r < \text{site}_{\text{width}};\ \ N_i^y - N_i^r > \emptyset\ ;\ N_i^y + N_i^r < \text{site}_{\text{length}} \#(1) - (4)$$

Second, $N_i$ cannot overlap with any existing circles in the array $D$. The logic adopts the Pythagorean theorem to determine whether two circles collide (**Eq. 5**).

$$\sqrt{(N_i^x - D_i^x)^2 + (N_i^y - D_i^y)^2} < (N_i^r - D_i^r)\#(5)$$

The positioning for $N_i$ is dependent on the location of $P_i$ (**Eq. 6 & 7**), where $\boldsymbol{\alpha}$ represents the angle between the centroid of $N_i$ and $P_i$.

$$N_i^x = \cos\alpha\,(N_i^r + P_i^r) + P_i^x\#(6)$$

$$N_i^y = \sin\alpha\,(N_i^r + P_i^r) + P_i^y\#(7)$$

At the beginning of the room plotting function, placement angle α is set equal to zero, resulting in $N_i^y$being set equal to $P_i^y$. To ensure that each $N_i$ fulfils the two constraints listed above, an increment of 0.01 (in radians) is added to α, causing $N_i$ to rotate around $P_i$ until both rules are satisfied.

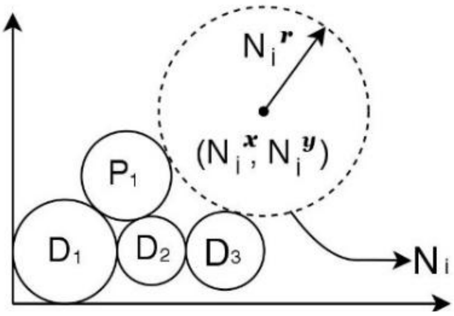


Fig. 2. Room plotting sequence sample

## 3.4 Machine Learning Algorithms for Space Optimization

To optimize the output and to transform the results to be more spatially efficient, theories of machine learning was applied to determine the optimal placement angle.

The method adopted is a common approach to Genetic Algorithm, where chromosomes of two parents are selected to produce children containing genes from both parties. To start off the search, a population {- π<**α**<π} is defined. In this scenario, the genes are represented by all **α** that were implemented in the plotting function and are stored in an array that can be mutated in increments of +/- 0.01. Since the goal is to achieve the smallest footprint while placing all rooms within the site, the fitness calculation is based on the bounding area that the current configuration. The smaller the area is, the higher the fitting score, and the more likely it is for its genes to be copied down. Conversely, if the total bounded area is larger than the previous generation, it is a less ideal candidate for reproduction.

To refine the mating pool, Elitism (e.g., Deb et al. 2007) is performed, meaning that the top 10% of the fittest population **α** goes to the next generation. Then, two parents are generated, through both selecting 50% each from the previous array randomly. The same logic applies to mating, where the child adopts 50% of the array from each parent randomly to produce the next generation. However, this optimized algorithm was stuck in the local minimum between two iterations, one that has excess dead space, and the other having overlapping polygons.

To achieve global optima efficiently, SA is introduced to improve the current circumstances. For a finite set of iterations, the value of bounding area is used to compare with its previous iteration. The objective is consistence with GA listed above, if the fitness score is higher, meaning that the bounding area is smaller, the value of the previous array **α** will take on the current array **α'**, which is chosen randomly. Inversely, if the fitness score is lower, whether α will take on the value of **α'** is dependent on the rate of probability **p**, which is calculated through Boltzmann probability factor (e.g., Ingber 1993). The benchmark for acceptance probability p is also randomly generated between ∅<**p**<1.0 to avoid termination at local minima (e.g., Ingber 1993).

## 3.5 Room Squaring

Circle diagrams are the schematic representations for room layouts. To generate a workable floor plan, the graphic must be transformed through shape-finding functions. The goal is to create realistic geometries that are pragmatic for construction. Since the centroids of each room, all required dimensions and adjacency relationships are stored in a central database, the process of producing straight-edged spaces is straightforward.

For each room $N_{\mathrm{i}}$, the existing centroid is maintained and the bottom, top, left, and right edges of the room polygon $\{N_{\mathrm{i}}{}^{B} = N_{\mathrm{i}}{}^{y}, N_{\mathrm{i}}{}^{T}, N_{\mathrm{i}}{}^{L}, N_{\mathrm{i}}{}^{R}\}$ are defined by adding or subtracting the radius $N_{\mathrm{i}}{}^{r}$ from the centroid as appropriate, for example (**Eq. 8**). This increases the room area but provides flexibility when overlapping walls are resolved in the next step. Overlapped edges are detected by looping through all rooms $N_{\mathrm{i}}$ and comparing to the remaining rooms $N_{\mathrm{j}}$, where j=i+1 to the total number of rooms and checking whether top right, top left, bottom right, or bottom left corners overlap with any of the other rooms $N_{\mathrm{j}}$. The rules (**Eq. 9a & b**) and resolution (**Eq. 10**) for a clashing top (of $N_{\mathrm{i}}$) and bottom (of $N_{\mathrm{j}}$) edges are shown below; identification and resolution of all other overlaps follow this logic. Finally, once all overlaps have been resolved, each room is tested (Eq. 11) to ensure that the area is maintained within acceptable tolerance.

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$$N_{\mathrm{i}}{}^{B} = N_{\mathrm{i}}{}^{y} - N_{i}{}^{r} \#(8)$$

$$N_{\mathrm{j}}{}^{T} > N_{i}{}^{B} > N_{\mathrm{j}}{}^{B} \#(9)$$

$$N_{\mathrm{j}}{}^{\mathrm{R}} > N_{i}{}^{L} > N_{\mathrm{j}}{}^{L} \#(9b)$$

$$N_{\mathrm{j}}{}^{T'} = N_{\mathrm{i}}{}^{B'} = \frac{N_{\mathrm{i}}{}^{B} + N_{\mathrm{j}}{}^{T}}{2} \#(10)$$

$$1.05 N_{\mathrm{i}}{}^{Area} \geq (N_{\mathrm{i}}{}^{T'} - N_{\mathrm{i}}{}^{B'}) * ( N_{\mathrm{i}}{}^{R} - N_{\mathrm{i}}{}^{L}) \geq 0.95 N_{\mathrm{i}}{}^{Area} \#(11)$$

Finally, rooms not achieving the area tolerance were adjusted (Eq. 10).

## 3.6 Room Import to BIM

To transform the room data developed above to architectural floor plans, visual programming language, Dynamo, was used to allow users to access the results through BIM software. Due to the fundamental deviation in programming languages – Dynamo uses IronPython and cannot recognize the more standard CPython – the polygons were extracted as a list that can then be read by Dynamo.

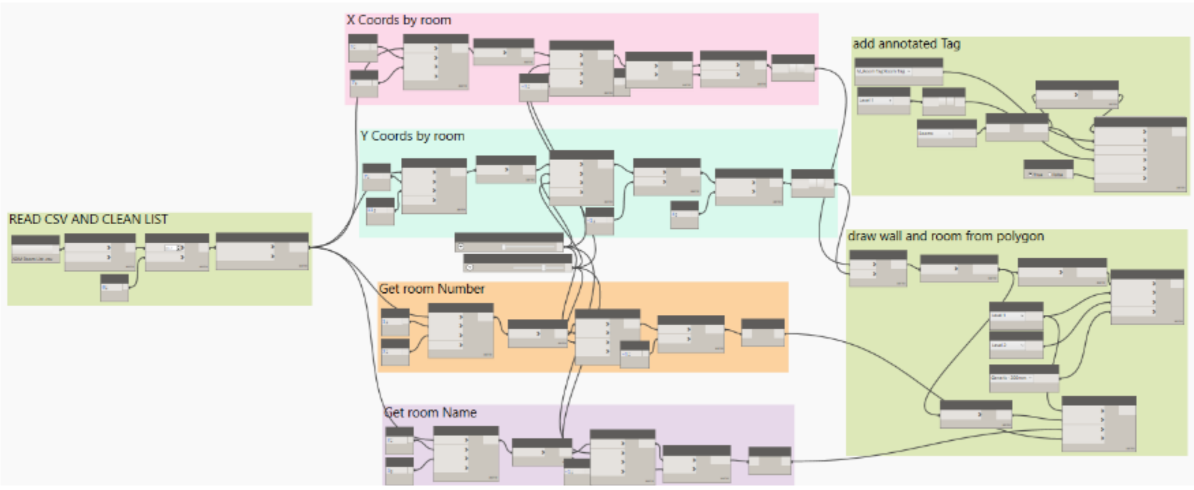


Fig. 3. Creation of rooms and generated polygons and mapping of room numbers using Dynamo.

## 4 RESULTS

The sequence of images shown (Fig. 4) highlights the results of each step in the room placement sequence. The result for attempt #1 (Fig. 4a) has the following errors: overlapping polygons, dead spaces, and circles that have exceeded the site boundaries (square in red). The total footprint of the bounded area is 792m$^2$. The optimization algorithm achieved a footprint of 730m$^2$ while satisfying both requirements of within site boundaries and having zero overlapping circles. Initially, only GA was for optimization, however, the proposed function was trapped in two local minima between two iterations: one with excess dead space, and the other having over-lapping polygons. To resolve this, SA was introduced, and its logical randomization approach assisted the searching process to be more accurate and efficient and resulted in a fully resolved and optimized layout (Fig. 4b). During squaring (Fig. 4c), significant overlaps were noted between all rooms and had to be resolved. Applying Eq. 8-11, 15 of 17 rooms achieved the 5% area tolerance, with the remaining two rooms at 6.50% and 7.25% above the required area, which is within the 10% tolerance typically used in practice. This resulted in a final, fully resolved layout (Fig. 4d) with a total room area of only 2% above the required area presented in the room datasheet.

The final floor plan (Fig. 5), implemented in Revit achieved all desired adjacencies, as it follows the adjacency matrix and size constraints of the original data input yet remaining a buildable geometry.

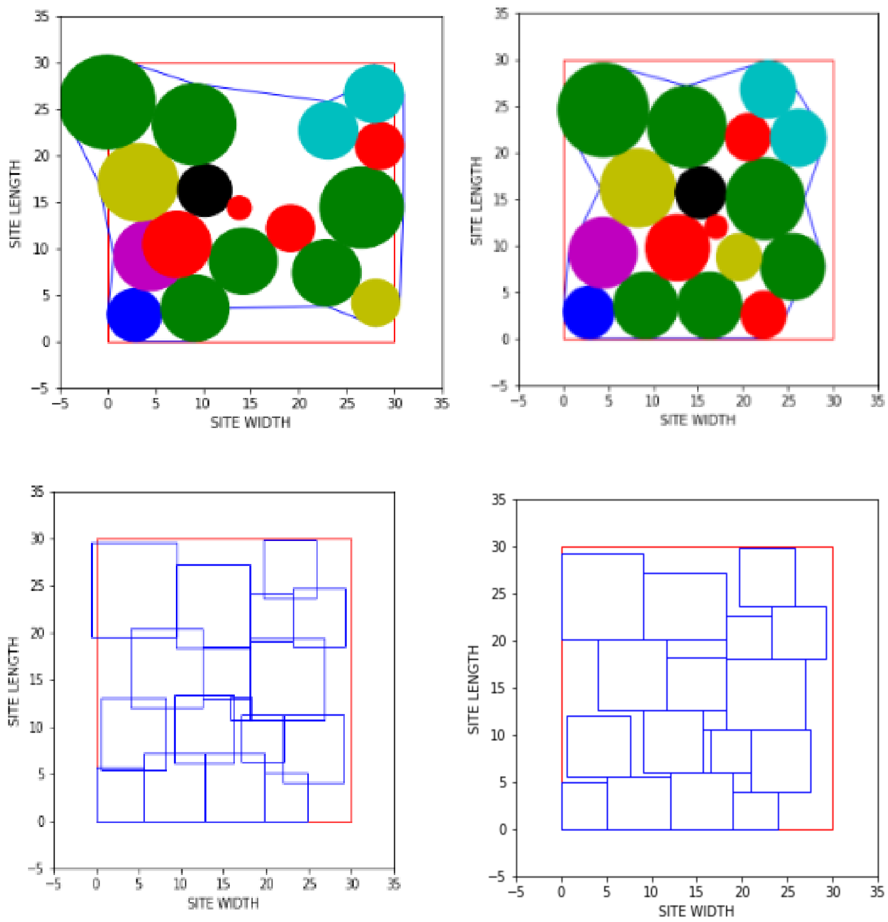


Fig. 4. Room placement and optimization sequence: Circle packing before (a; top left) and after optimization (b; top right); squared rooms with (c; bottom left) and without overlap (d; bottom right)

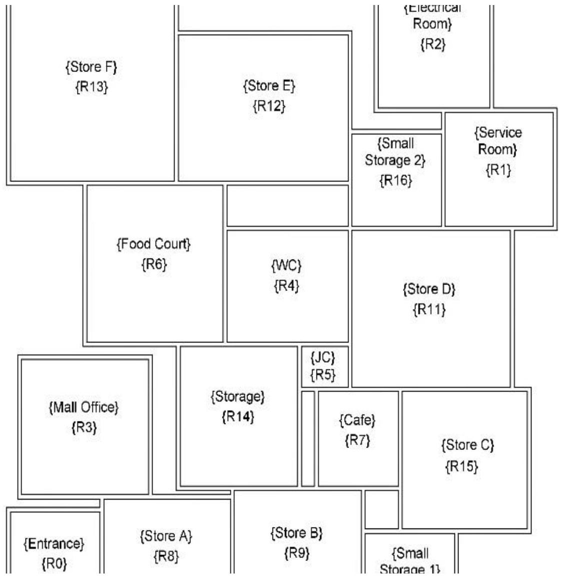


Fig. 5. Creation of rooms from polygons generated and mapping of room numbers using Dynamo

## 5 Discussion and Conclusions

From room datasheet to BIM, this researched has achieved a streamlined approach to room-planning under the assistance of visual programming language and two automated optimization algorithms. The current gap in existing studies is the disconnection between research and applications. Most of the functions have only been tested within the research team, since examples such as circle-packing and GA/SA optimization algorithms were initially developed to solved mathematically problems. Without considering room-planning in a real-life setting, the logic developed cannot be proven to be reliable and beneficial within the industry. In this paper, techniques were refined and tested using a small-scaled architectural prototype. The results obtained have shown the realistic performance of the approaches adopted, displaying the adaptability of this research and the great potential it acquires.

By combining the circle room plotting sequence with machine-learning algorithms, the intention to achieve the most compact configuration was realized. Through the room datasheet, users had absolute control over the required rooms, dimensions, and the adjacency matrix, while retaining the benefits of an algorithm-assisted decision-making design. The room plotting sequence provides architects with an accurate visual representation of the most spatially efficient layout within a shorter timeframe, particularly when designing large-scaled projects with repetitive unit types. With the assistance of automated design tools, laborious tasks can be relinquished to computer programs, freeing designers to focus on creative ventures.

A limitation of this approach is that it is not yet seamless. This is primarily be-cause machine learning packages are not usable within Dynamo and required the use of Python and export of polygon coordinates to for import into Dynamo. A second limitation is the rigidity of the fitting function. Since the bounding area is the only measure of success, outcomes of the optimization had omitted other aspects of the space. Finally, consistent with the majority of previous studies, this algorithm considered only a single level. The extension of this work to multiple floors is desirable and should be developed in future research. Future research should also focus on holistic approaches when applying generative design tools for construction projects, such as incorporating circulation spaces and building code compliance evaluation. Alternative fitting functions and multi-objective should be considered to suit different needs depending on the functionality of space, for example, energy optimization and/or minimized travel distances.

The practical implications of this work are significant. For architects, layout automation tools can increase the efficiency in the preliminary stage of design. Traditionally, during massing studies, where building footprints are constantly under revision, hours of works were poured into the monotonous routine of mapping out all required programs within a confined space. With the assistance of optimized room-planning technique, the most compact floor layouts can be created automatically, and ready to be used in BIM right away. With the significant decrease in time spent on repetitive tasks, architects can explore a broader range of potential building footprints and floorplates to optimize energy performance, and focus on the occupant experience of the space, thus enhancing overall design quality.

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# BUILDING A NEXT GENERATION AI PLATFORM FOR AEC: A REVIEW AND RESEARCH CHALLENGES

**Zihao Wang[1]*, Bingzhen He[2]*, Yu Yang[3], Charles Shen[4], and Feniosky Peña-Mora[5]**

**Abstract:** Transformation of the AEC industry has been found to face significant and persistent hurdles both internal and external to the industry, such as industrial fragmentation, difficulty in talent recruiting, inadequate collaboration and knowledge transfer. Meanwhile, advances and maturity in digital technologies recent years offer tremendous potential to tackle these challenges. Examples include Artificial Intelligence (AI) and deep learning, computer vision, big data analytics, Building Information Models (BIM), 3D scanning, Augmented Reality (AR), Unmanned Aerial Vehicles (UAVs), autonomous driving, and blockchain.

We envision that the next generation platform for the AEC industry shall integrate this diverse list of digital technologies. In this paper, we review the state-of-the-art in related literature aiming at creating such an integrated platform. Our review is organized into the following four themes, and for each of them, we also identify gaps and challenges.

1. AI-based BIM model generation: this topic addresses how to make BIM models more ubiquitous, which includes the automatic generation of As-planned BIM model from 2D drawings and the automatic generation of As-built BIM model from site images/videos and point clouds.
2. Blockchain-based collaboration: this theme explores the possibilities of applying Blockchain for AEC to improve various essential aspects such as trust in multi-party collaboration and contract enforcement.
3. AR-based visualization: this topic studies the AR-based visualization for construction management, which aims to increase the efficiency of information transmission.
4. AI-based Construction management: this area reviews the application of AI in progress monitoring, safety management, quality management, and contract management.

Based on the above analysis, we conclude by outlining potential topics of a research framework for creating a next generation AI platform for AEC.

**Keywords:** Artificial Intelligence, BIM, Blockchain, Augmented Reality, Construction Management.

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# 1 INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry is one of the largest industries in the world; yet it is also known to have the lowest productivity gains of any industry in the past decades. World Economic Forum (WEF, 2016) reports estimate that a 1% rise in the construction industry productivity worldwide could save $100 billion a year.

Nowadays traditional construction management is facing a series of challenges. It is expensive and time consuming for managers to monitor project performance (Pučko et al. 2018). It is difficult for managers to monitor projects in real time (Navon and Sacks 2007). Another problem is the trust and transparency crisis between the parties in the project (Hargaden et al. 2019). Meanwhile, due to the lack of visualization technology, site information cannot be transmitted to managers effectively, which may lead to potential mistakes in decision making (Sun et al. 2020).

In the past few years, researchers have tried to address these challenges by introducing digital technology into the AEC industry, including Artificial Intelligence (AI), Computer Vision, Building Information Modeling (BIM), Blockchain, Augmented Reality (AR), etc. Artificial Intelligence (AI) is defined as the intelligence of machines, i.e. replicate human intelligence via artificial technologies to invent intelligent machines (Minsky 1960; Mohasses 2019). In the AEC industry, AI technology becomes popular in resolving problems or improve performance in construction projects, e.g. machine learning, which is increasingly employed in project delay risk prediction (Gondia et al. 2019), facility life-cycle cost analysis (Gao et al. 2019), etc. Deep learning is one sub-domain of machine learning which applies deep neural networks in task learning. Integrated with computer vision, deep learning has been used in safety management (Fang et al. 2020), progress monitoring (Lei et al. 2019), and 3D model reconstruction (Che et al. 2019). Building Information Modelling (BIM) is an information management system of buildings during their full lifecycle (Delgado et al. 2018). The application of BIM promotes the booming of the AEC industry, as it helps improve the efficiency and reduce costs by developing virtual 3D models and effective management systems with rich information. Blockchain, which originates from Bitcoin (Nakamoto 2008), is a distributed public ledger that the data, assets and transaction records can be shared among participants in the network to achieve mutual-trust networks (Hargaden et al. 2019). The potentials of applying blockchain have been explored across some construction domains, e.g. construction supply chain (Tezel et al. 2019). Augmented Reality (AR) is the interaction between the artificial elements generated from digital devices and the real-life environment (Mitha et al. 2013). Now, AR has already been used in progress monitoring (Ratajczak et al. 2019) and defects detection (Lee et al. 2012). However, existing technologies are still fragmented and require integration to perform efficiently in construction management.

This paper provides a literature review and organized these advanced technologies into a next generation AI platform for the AEC industry. The current states of various management to be achieved by the platform are reviewed as well as the possibility of applying AI technology. Meanwhile, existing challenges and future works are discussed. Section 1 gives an overview of related technologies; Section 2 presents the details of the research method; Section 3 shows a review of the technologies that contribute to the next generation AI platform and current states of construction management; Section 4 concludes the work in this paper.

## 2 METHODOLOGY

The major databases used by this paper include Web of Science, ScienceDirect, ASCE, IEEE, Google Scholar. In the literature search, we used different sets of keywords for different topics to obtain a list of related publications (See Table 1). By limiting the publication data from 2014 to the present, the publications that represent the latest research findings are collected. This review focuses on journal articles and conference papers in artificial intelligence, computer vision, civil engineering, and construction management. To select highly related publications, the collected publications are then filtered through reading abstracts and conclusions to exclude the papers that are not related to construction management. After the two-step searching and filtering, a total of 225 academic papers are selected. Due to space constraints, this paper is unable to present a complete review. Therefore, we select a part of these papers (84 papers) to review.

Table 1: Overview of Literature Search

| Topic | Keyword | No. of Papers |
|---|---|---|
| As-planned BIM Model Generation | 2D drawings, BIM, floor plan, AI | 14 |
| As-built BIM Model Generation | Point clouds, construction, BIM, machine learning, deep learning, registration, segmentation, classification, 3D reconstruction | 90 |
| Blockchain-based Collaboration | Blockchain, AI, IoT, smart contract, BIM, construction | 20 |
| AR-based Visualization | Augmented reality, AI, construction management | 21 |
| AI-based Construction Management | Machine learning, deep learning, progress monitoring, construction safety, quality inspection | 80 |

## 3 NEXT GENERATION AI PLATFORM FOR AEC INDUSTRY

In this paper, we reviewed the advanced technologies relating to the next generation of AI platforms for the AEC industry. This paper will follow the structure of Figure 1 to review.

- In section 3.1, this paper reviews the methods of input data acquisition.
- In section 3.2, the generation of BIM model is reviewed, including As-planned BIM model generation (Section 3.2.1) and As-built BIM model generation (Section 3.2.2).
- In section 3.3, blockchain-based collaboration is reviewed.
- In section 3.4, this paper reviews AR-based visualization for construction management.
- In section 3.5, this paper reviews AI-based construction management, including progress management (Section 3.5.1), safety management (Section 3.5.2), quality management (Section 3.5.3) and contract management (Section 3.5.4).

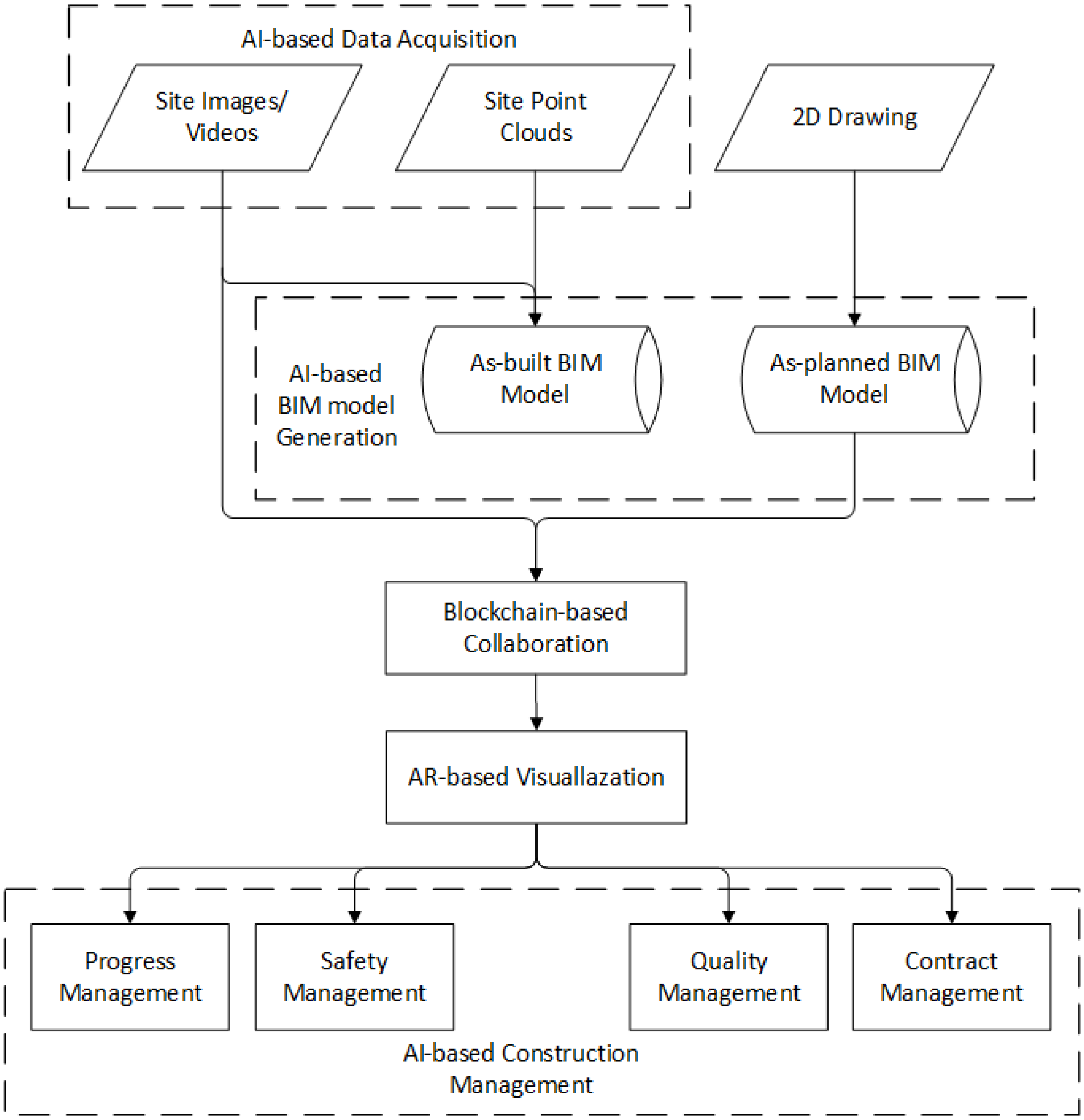


Figure 1: Next Generation AI Platform for AEC industry

## 3.1 AI-based Data Acquisition

Most of the papers reviewed in this paper require site images/video or point clouds as input. Manual-based data acquisition methods are time-consuming and costly. Unmanned aerial vehicles (UAVs) as a new technology can collect image data in the inaccessible areas or undertake tasks that are dangerous to human beings (Shang and Shen 2017), which is more efficient and cost-effective. More importantly, the images collected via UAVs can provide sufficient visual coverage overlaps of the site to support the generation of 3D building models, which is critical for automated progress monitoring. However, it is still a challenge to achieve autonomous path planning and navigation for UAVs (Ham et al. 2016). Some studies have explored the potentials of applying AI in autonomous path planning (Aggarwal et al. 2019; Hamledari et al. 2018). For instance, according to Hamledari et al. (2018), swarm intelligence was employed in making the UAVs inspection plan, which reduces the flight duration and thus improves the efficiency of site inspection. Besides, some studies integrated 4D BIM with UAVs-enabled 3D reconstruction to achieve autonomous path planning of UAVs (Shang and Shen 2017). Using 4D BIM as a prior model, together with ray-tracing to detect visible elements, the optimal flight missions can be created at locations where have expected changes to optimize the visual coverage of the flight plan (Ibrahim and Golparvar-Fard 2019). However, the automatic integration of as-built conditions into 4D BIM is still a primary challenge for UAV-based inspection (Hamledari et al. 2017). To resolve this challenge, Hamledari et al. (2017) utilized industry foundation classes (IFC) schema to achieve automatic integration of UAV-based as-built inspection results into 4D BIM.

## 3.2 AI-based BIM Model Generation

As-planned BIM model shows the proposed progress and As-built BIM model shows the actual progress (Son et al. 2017). These two models are used as inputs in progress management (Golparvar-Fard et al. 2010). In this section, the automatic generation of As-planned BIM models and As-built BIM models will be reviewed. We also discussed the limitations of current technologies.

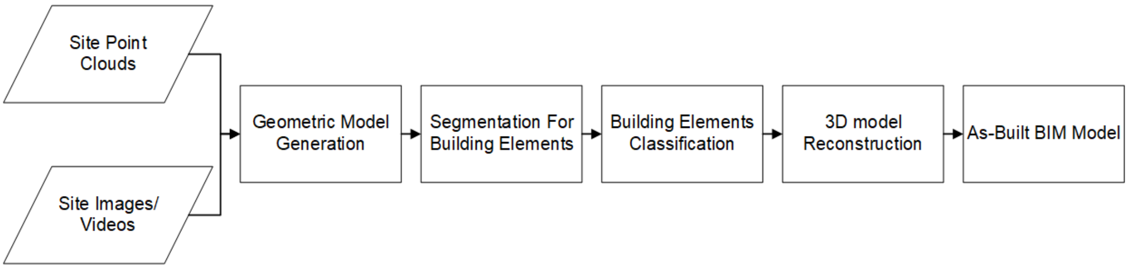


Figure 2: BIM Model Generation Workflow

### 3.2.1 As-planned BIM Model Generation

BIM models can bring tremendous benefits to the AEC industry, but traditional BIM models rely on manual generation (Seyis 2019). To solve this problem, the idea of automatically generating BIM models was proposed. Nowadays there are several methods to generate As-planned BIM model through 2D drawings (Cho and Liu 2017; Lim et al. 2018). However, some challenges exist, e.g. low accuracy of automatic recognition, heavy manual workload (Liu et al. 2017).

Deep learning is used for further automation. A method based on deep learning and integer programming to restore geometric and semantic information of floor plans was proposed (Liu et al. 2017). This method achieved 90% accuracy, higher than other methods in the same period. However, this algorithm lacks robustness for unseen elements. A deep multi-task neural network was proposed to identify room types and walls (Zeng et al. 2019). Compared with the Raster-to-Vector algorithm (Liu et al. 2017), this algorithm has higher precision. And it can handle more complex floor plans, including irregular shaped rooms and curved walls. The identification results can be further used for 3D reconstruction. However, this method lacks accuracy for inside and outside region identification and requires a larger dataset for training to deal with the diversity of floor plans.

At present, deep learning-based BIM model generation from 2D drawings is still facing some problems. Firstly, the training database is relatively small compared with training databases in other fields of computer vision. Meanwhile, the establishment of databases still rely on manual work. Secondly, the accuracy and generality of the current algorithm needs to be improved. Thirdly, most of the algorithm focus on 2D drawing recognition and vectorization. Finally, BIM models generated from 2D drawings lack schedules.

### 3.2.2 As-built BIM Model Generation

The procedure of converting vision-based data (e.g. images, videos) to the as-built BIM model is referred to as Scan-to-BIM. The typical workflow involves four steps: 1) Geometric model generation; 2) Segmentation for building elements; 3) Building elements classification; 4) 3D model reconstruction. Firstly, by registering multiple laser-scanning point clouds or generate point clouds from a series of images, a geometric model is built. In the second step, the registered point clouds are segmented into many clusters that have similar properties. In the third step, each cluster is assigned to a class label based on geometric and contextual features observed. With geometric and contextual features, the clusters can be converted to various 3D objects, e.g. wall, windows, floor. The fourth step involves the splice of 3D objects to a realistic BIM model based on different spatial relationships. Then, some other non-metric attributes like types of materials are added to the individual BIM elements. A 3D BIM model is reconstructed successfully. Accurate as-built models can help achieve automatic progress monitoring and contract execution.

(1) Geometric Model Generation

The input of geometric reconstruction can be classified into point clouds and images. Laser scanning can generate a dense and accurate point cloud, but it also needs professional technicians and expensive equipment (Asadi et al. 2019). For images as inputs, Structure-from-Motion (SfM) and Multi-View Stereo (MVS) are used for reconstruction, which can be got from cheaper digital cameras, become possible (Han et al. 2018).

Deep-learning-based approaches were introduced to try to replace traditional methods in point cloud registration. Based on PointNET (Qi et al. 2017) algorithm, PointNetLK combined the LK algorithm (Lucas and Kanade 1981) which was used for image alignment to register (Aoki et al. 2019). PoinNetLK is more efficient in computing large-scale point sets and it shows good applicability when facing the untrained shape. Deep Closest Point (DCP) algorithm (Wang and Solomon 2019) used a learning-based method to solve the problems existing in the ICP (Besl and McKay 1992) algorithm. When using the ModelNet40 database to test, the DCP algorithm is robust when facing the noise, and its accuracy is higher than PointNetLK (Wang and Solomon 2019). Another method used 3D-CNN and 2D-CNN for coarse registration and fine registration respectively (Chang and Pham 2019). For accuracy, this method is close to RANSAC + ICP algorithm, and its efficiency is 15 times that of RANSAC + ICP algorithm.

In image-based 3D reconstruction, deep-learning-based SfM algorithms are used to solve depth and motion. DeMoN is a convolutional network with an iterative structure (Ummenhofer et al. 2017). However, DeMoN can only handle one image pair, which limits its use. DeepTAM extended the input to multiple images and achieved better performance than DeMoN (Zhou et al. 2018). Other algorithms include DeepSFM (Wei et al. 2019), ENG (Dharmasiri et al. 2018), etc. The accuracy of all these methods is higher than the SIFT-based method.

For MVS, deep-learning-based MVS includes, DeepMVS (Huang et al. 2018), MVSNet (Yao et al. 2018), R-MVSNet (Yao et al. 2019), etc. DeepMVS performed better than the non-learning algorithm COLMAP (Schönberger et al. 2016) in the test. However, it only generates depth maps and still needs post-processing. R-MVSNet (Yao et al. 2019) tried to solve the scalability problem in MVSNet (Yao et al. 2018) by using gated recurrent units to regularizes the cost volume. R-MVSNet (Yao et al. 2019) achieves better reconstruction completeness and overall quality. However, the depth maps fusion algorithms in MVSNet (Yao et al. 2018) and R-MVSNet (Yao et al. 2019) are not using deep learning.

(2) Segmentation for Building Elements

After obtaining the complete point clouds of the building from site images/videos or point clouds fragments, the building elements need to be generated. In segmentation, point clouds are segmented into separate point clusters with similar properties based on non-semantic information (e.g. location, geometry, intensity). Some popular machine learning approaches for segmentation include K-nearest neighbors (KNN) and Principal Component Analysis (PCA). The segmentation process laid a foundation for the processing and analysis of each segment or object with richer information, e.g. geometric features and contextual features of objects. However, there is no deep learning-based approach for segmentation, which requires further research on it.

(3) Building Elements Classification

After segmentation, the building elements can be generated and identified. In classification, each cluster is assigned to a class ("label") based on different criteria. Some features need to be extracted to describe point clouds, e.g. geometric and contextual features (Che et al. 2019). Geometric features describe local attributes of building elements, e.g. shape, size. Contextual features involve the various relationships among building elements (e.g. proximity), which makes the classification more robust (Bassier et al. 2019; Che et al. 2019). Since AI technology becomes increasingly popular in recent years, machine learning (ML) is employed in the classification of point clouds as a classifier. Support Vector Machines (SVM), Decision Trees, Random Forest (RF), and Neural Networks (NN) are popular models in classification.

SVM performs well in classifying indoor and outdoor point clouds. In the study of Perez-Perez et al. (2019), SVM was used to extract the relationship between semantic and geometric labels for the following classification of segments into semantic categories. Their method pioneeringly identifies beams and columns automatically in a Scan-to-BIM process with average fitting error of 0.633 mm. However, this approach is highly dependent on the performance of the segmentation method selected. Random forest (RF) consists of multiple decision trees and allows them to select the most popular class (Breiman 2001). In the study of Park and Guldmann (2019), the RF algorithm was employed to classify LiDAR points into four different categories of building elements, reaching a high accuracy (96.5%). RF classifier is more robust to the quality of training examples and overfitting than other ML classifiers (Belgiu and Drăguţ 2016). However, the sample imbalance among different object classes can affect RF performance, which causes the issues of over- or under-representation of certain classes (Belgiu and Drăguţ 2016).

Deep learning has been considered for the classification of building elements due to its good performance (Che et al. 2019; Chen et al. 2019a; He et al. 2016; Czerniawski and Leite 2019). Although deep learning bypasses manual feature descriptors (Chen et al. 2019a), regular and structured data are required as input, e.g. 2D images. Therefore, there are two main categories: 1) 2D image-based classification (Lawin et al. 2017); 2) 3D voxelization (Maturana and Scherer 2015). In 1), the point clouds are projected or rasterized to 2D images, while the data are voxelized to 3D grids in 2). Both two directions mainly use Convolutional Neural Networks (CNNs) as architecture. Lawin et al. (2017) used 2D images to achieve classification of 3D point clouds. They firstly projected 3D point clouds onto synthetic images and then projected the prediction scores obtained from 2D CNN (fed synthetic 2D images) back to the point clouds to achieve the classification. Maturana and Scherer (2015) integrated 3D CNN with occupancy grid (named "VexNet") to identify objects like chairs. However, for 3D voxelization, occlusions and clutters impede the object-level segmentation. Besides, it is more complex to use voxel grids as input format, which leads to the loss of accuracy. Moreover, point clouds can be directly used as input but cannot clearly define object boundary except using bounding boxes (Chen et al. 2019a; Qi et al. 2017). Therefore, this method performs well only under the condition that objects are separated from the background, e.g. outdoors.

Both machine learning and deep learning need large datasets of labeled objects for training. Currently, the building elements are labeled by manual work, which is labor-intensive and time-consuming (Perez-Perez et al. 2019; Wang et al. 2015). 4D BIM is one possible solution. BIM as a semantically rich model is used in semantic labeling and classification by transferring semantics from BIMs to point clouds. In the study of Braun and Borrmann (2019), as the as-planned BIM model is aligned with the generated point clouds, each BIM element could be projected onto the point clouds. This ensures a precise process of establishing a dataset of labeled building elements. Czerniawski and Leite (2019) extracted the geometry and attached semantics from BIMs and then attached them to the laser scanning data to create a large labeled dataset for training deep neural networks (DNN), which avoids the step of the dedicated annotation.

(4) 3D Model Reconstruction

Once the point clouds have been classified into different categories of building elements, the 3D model reconstruction starts. All the identified building elements are connected and assembled to 3D BIM models. This process needs to consider different spatial relationships, including aggregation (i.e. part of, belong to, etc.), topological (i.e. connected to, inside, outside, etc.), and directional (i.e. above, below, etc.) relationship (Bassier et al. 2019; Hichri et al. 2013). For example, Nguyen et al. (2005) showed an automatic way to deduce topological relations among building elements. Besides, other studies also represented identified objects in IFC format to establish topological relations (Macher et al. 2017). Moreover, Tran et al. (2018) presented a shape grammar approach to generate indoor 3D models with rich topological relations. Apart from spatial relationships, some non-metric attributes are added to individual building elements. These attributes enrich the description of the elements, including the information of materials, historical records, economic data, etc (Hichri et al. 2013). Although no deep learning-based approach is applied in the final reconstruction, some processes can potentially employ deep learning algorithms, e.g. the process of splicing based on spatial relationships.

In the BIM model generation phase, knowledge is still fragmented. At present, it lacks an end-to-end algorithm to directly realize the generation of BIM models. Noise and occlusions are a major challenge for Scan-to-BIM. The current state-of-the-art algorithms show robustness to Gaussian noise, but their performance still needs to be improved when facing a higher level of noise. Occlusions are inevitable in data collection. At present, there is still no effective method to recover the actual state of the object from occlusions. Another challenge is the scalability of the algorithm. The employment of 3D CNN leads to an increase of cost volume. Many algorithms are limited by the size of memory, so they cannot be applied to large scale reconstruction. The generalization capability of the algorithm also needs to be addressed. AI-based algorithms need to be trained by using existing datasets, which are often standardized. But the diversity of architectural design makes it difficult to set up a dataset which concludes all kinds of design and elements. Therefore, the algorithm needs to have a strong generalization ability to face the non-standardized building.

## 3.3 Blockchain-based Collaboration

Blockchain has the potentials to resolve the problems in construction projects, e.g. poor regulation compliance, inadequate collaboration, and complex payment practices (Li et al. 2019a). With the integration of BIM and IoT, blockchain can achieve a smart and transparent collaboration platform with advanced functions for construction management, e.g. automated progress monitoring (AI technology) and contract execution (smart contract) (Li et al. 2019a), which significantly reduces the management cost and improves the efficiency of processing.

Some researchers have explored the potentials of integrating blockchain with AI in the AEC industry. Tang et al. (2019) proposed a framework with the integration of blockchain, BIM, IoT, AI, big data. In this framework, based on the data collected by BIM model and IoT sensors, AI algorithms can be used in automated decision making to achieve smart project monitoring. Blockchain can record the decisions and progress updates and ensure the immutability and traceability of data (Singh and Ashuri 2019). Moreover, AI was also considered integrated with blockchain and smart contracts in automated code compliance checking processes (Nawari and Ravindran 2019b). AI can extract related information from regulations into rules automatically, while blockchain guarantees the reliability of the extracted information and the activities of transferring. However, few frameworks have been designed and implemented in real projects (Singh and Ashuri 2019).

Blockchain is in the early stage of development and thus has numerous future works to do. Despite the benefits it would bring to the AEC industry, blockchain is still facing some challenges. Firstly, it is difficult for blockchain and AI to be adopted rapidly by the traditional industry, since the existing mechanism has run well for decades or even hundreds of years. Secondly, there is no actual design for the integration of blockchain and AI technology currently, and the use case for it is even further away. Thirdly, the costs of transferring to the new style from the traditional mechanism are unpredictable and whether it is worth remains to be seen. Furthermore, most research focus on the financial or transaction part of the construction projects, while few researches pay attention to the design and construction part. This part needs high reliability and traceability of the information delivered to guarantee the key criteria of projects (time, cost, quality) and the liability distribution of involved parties. Therefore, there are still lots of work needed to do in the future.

## 3.4 AR-based Visualization

The development of augmented reality (AR) technology provides tools for construction visualization. Golparvar-fard et al. (2010) superimposed the BIM model with the site photos, and showed the difference between the construction progress and the planned progress by using color code. Zollmann (2014) developed an AR system that supports construction site progress monitoring and recording, but it relies on specific hardware. In AR4C system, exclude progress, KPI information is also showed (Ratajczak et al. 2019).

AR technology is also used for defect detection (Lee et al. 2012). ARCam was used for the inspection of steel columns but still had accuracy problems. Park et al. (2013) mapped the BIM model to the site through a marker-based AR system to help the workers confirm the task, and give feedback to the manager. Lamsal and Kunichika

(2019) used AR marker points and structure sensor SDK to register AR images. This system is used to help workers check their work through the iPad to prevent mistakes.

In AR, deep learning was used for localization. Through using CNN, real-time images can be compared with BIM rendered images to achieve indoor localization (Ha et al. 2018). An AR system based on this method was used for facility management (Baek et al. 2019). Localization can also be achieved by calculating camera pose.

Fast and accurate localization is a problem for AR technology. Due to limited performance, AI-based methods are difficult to be applied to mobile devices (Li et al. 2019b). The current AR system can only display limited information. In the assumption of this paper, AR can be used to display more construction information, such as material list, schedule, construction drawings, etc. Meanwhile, the current system lacks interactivity. When managers click on architectural elements on the screen, more details should be provided.

## 3.5 AI-based Construction Management

### 3.5.1 Progress Management

Automated progress monitoring is achieved by using AI to compare as-built and as-planned BIM model. Comparison methods include geometry-based methods and image-based methods, which can also be used in combination (Han et al. 2018).

For geometry-based progress monitoring, the first step is to align the models. This step can be done by aligning two point clouds, which is similar to the point cloud registration process. In section 3.2.2 (1), we have discussed the point clouds registration algorithm based on deep learning and explained its advantages. After the alignment, by performing different operations on the two models, progress can be identified. In this process, an identification threshold needs to be set for each building element, so that when the occupancy of the as-built model reaches a certain level, the element is recognized as completed (Golparvar-Fard et al. 2010). This process can be abstracted into a classification process in which AI technology can be used. SVM has been already used as a classifier in this process and has 82.89% detection accuracy (Golparvar-Fard et al. 2010).

In addition to geometric methods, progress monitoring based on appearance can also be used. When the corresponding materials are identified in both models, the construction progress is detected (Han and Golparvar-Fard 2014). An image-based progress detection algorithm was proposed (Han and Golparvar-Fard 2014), which detects the progress state through the recognition result of the SVM classifier. Another paper also used this method for progress monitoring (Han and Golparvar-Fard 2015). The result showed that the accuracy reached 95.6% (Han and Golparvar-Fard 2015).

For the application of AI in progress management, some challenges exist. Existing progress monitoring techniques rely on the compartment between as-planned models and as-built models, so it faces similar challenges like occlusions, noise, etc. Progress monitoring is not accurate when as-planned models lack details (such as lack of formwork, shoring, etc.). Meanwhile, the existing monitoring technology only used the low-level knowledge, construction sequencing and other high-level reasoning is not used.

### 3.5.2 Safety Management

Safety is always a significant topic in the AEC industry (Nath et al. 2020). Current research focus on various fields (Fang et al. 2020): failure of wearing Personal protective equipment (PPE) (Fang et al. 2018; Wu et al. 2019), unsafe behavior (Ding et al. 2018;

Fang et al. 2019), and exposure to hazardous area (Roberts et al. 2017; Zhang et al. 2019). Integrating with computer vision and AI technology, vision-based approaches have become more popular (Nath et al. 2020). It uses cameras to record site images or videos, and then analyzes them by to detect unsafe conditions.

(1) Failure of wearing PPE

Failure of wearing PPE has become one of the main reasons for injuries accidents on construction sites (Li et al. 2017). One approach uses handcrafted features extracted from images or videos to automatically detect the PPEs wearing, e.g. Histogram of Oriented Gradients (HOG) (Dalal and Triggs 2005). Fang et al. (2018) employed Faster R-CNN to automatically detect the non-hardhat-use (NHU) of construction workers. Despite the low precision for identifying the hardhat under the impact of occlusions, the recognition precision and recall rates were consistently over 90%. However, the heavy dependence on the information from upper features might do harm to the performance at different scales in the images. To resolve these problems, Wu et al. (2019) employed a single-stage approach based on the SSD framework to detect hardhats worn by workers, which uses a single CNN to create bounding boxes.

(2) Unsafe Behavior

Unsafe behavior of workers leads to around 88% of the accidents on site (Ding et al. 2018). Ding et al. (2018) integrated Long Short-Term Memory (LSTM) model (Hochreiter and Schmidhuber 1997) with CNNs to identify the potential unsafe behaviors of workers such as climbing a ladder. The accuracy of detecting safe and unsafe behaviors was 97% and 92% respectively, which exceeds the performance of other common methods like HOG by about 10% on average. In addition, R-CNN was also employed in Fang et al. (2019) to detect workers traversing structural supports during construction. As a result, the precision and recall rates reached 75% and 90% respectively. However, occlusions and overfitting still influence the results figured out by the model.

(3) Exposure to Hazardous Area

Exposure to hazardous area is another reason for construction accidents. Some sensor-based approaches are used, integrating with AI technology. Zhang et al. (2019) used smartphones to detect near-miss falls by analysing the acquired data with ANN. As a result, the average precision and recall rates were around 90% and 91% respectively. Concerning vision-based approaches, in Roberts et al. (2017), CNN was employed to identify crane locations in real-time for the avoidance of safety hazards to their surroundings on construction sites.

Some state-of-the-art models have been developed such as Faster R-CNN, which have good performance in vision-based safety detection under various visual conditions of the construction site. However, there are still some challenges that need to be resolved. Firstly, large datasets are needed to train deep learning models, since existing public datasets of unsafe behaviors in construction are not as large as meeting the requirement of training. Secondly, similarly to vision-based 3D reconstruction, occlusions are also the major challenge that affects the performance of proposed detection models. If workers are partially occluded, the precision of detection reduces significantly. One possible solution is to install multiple cameras on the construction sites to achieve full site coverage. Thirdly, there is no standard to evaluate the performance of detection. As different studies use different training datasets with various samples or criteria, it is difficult to compare the performance of different methods. The lack of standard may lead to discrepancies among the evaluation criteria of unsafe behaviors or conditions.

Therefore, a widely accepted standard shall be developed for the evaluation of construction unsafety detection. Moreover, a deeper or detailed detection is required (e.g. whether to wear PPEs correctly) since most methods just achieve the basic detection (e.g. whether to wear PPEs or not). In addition, although current methods achieve real-time safety management, it may be not enough to prevent accidents. There is a need for the models that can predict these unsafe conditions in the early time and the alarming mechanism that reflect the predictions to related personnel effectively.

### 3.5.3 Quality Management

AI-based image detection technology is proposed to replace manual detection. According to the different objects, defect detection can be classified as sewer detection (Cheng and Wang 2018), tunnel detection (Makantasis et al. 2015), road detection (Zhang et al. 2017), building detection (Perez et al. 2019), etc.

CNN is one of the networks which has been used in detection. Perez et al. (2019) used CNN for building detection, which could identify mould, ruff, and stain. A new algorithm CrackNet, which uses CNN without pooling layers, was proposed to detect asphalt pavement cracks (Zhang et al. 2017). Compared with the traditional SVM algorithm, the accuracy and F-measure of this algorithm are better. A tunnel detection technique used CNN to extract defect characteristics and classify them by MLP (Makantasis et al. 2015). The detection rate of this method reached 89%, better than ANN, SVM, KNN, and Ctree.

Faster R-CNN is another popular algorithm, which solves the generation of region proposals (Ren et al. 2015). Cheng and Wang (2018) used it to detect four types of defects in sewer. Cha et al. (2018) used Faster R-CNN to identify concrete and steel. Compared with the traditional CNN method, this method has a better performance in locating defects. To sum up, deep learning has shown good performance in defect detection.

AI-based defect detection is facing the challenge of lacking a large database for training. Meanwhile, a single quality recognition model can only detect limited types of quality defects. There is no generic model that can detect all types of defects simultaneously. What's more, prior technologies are image-based which means they cannot be applied to recognize defects that are not visible.

### 3.5.4 Contract Management

Contract management is defined as the process that manages the creation and execution of contracts efficiently (Chen et al. 2019b), which is complex since it involves various stakeholders (e.g. contractor, client, engineers, government, etc.). Smart contract, a computer protocol that aims to enforce contracts in a digital way, makes automated contract execution possible (Di Giuda et al. 2020). For example, a term of contract can be written in code and automatically executed by linking related records from government agencies (e.g. government regulations) to blockchain standards (Mason 2017). In addition, once the defined obligations have been completed, the payment function of smart contracts will be executed automatically to pay related contractors for the completed work (Di Giuda et al. 2020). Even further, AI can be used to develop an engine that helps people make decisions based on the information received. For example, the AI engine can decide whether the project continues under different weather conditions based on information from meteorological department and related contract terms. However, there are some limitations of the application of smart contracts, e.g. the inherent security vulnerabilities of the input of evidence of fulfilment, machine-readable script of contract that should be able to be reviewed and verified by experts (Nawari and Ravindran 2019a).

## 4 Conclusions

This paper reviews techniques that contribute to the development of next generation AI-based platform and the revolution of construction management field. Nowadays, the application of AI technology to various practices in the AEC industry brings convenience and improve efficiency for the management work during the real-life construction projects. With the integration of AI, big data, BIM, AR/VR, and blockchain, the platform has great potentials to lead a new revolution in the AEC industry. The automated generation of 3D as-planned and as-built models significantly reduces the time and costs required for drawings and model production, and thus decreases the risks of delay and cost overruns. With the integration of blockchain technology, the AI-based platform can achieve an immutable and traceable documentation mechanism, which resolves the problems of lack of trust in traditional construction projects. The application of AR technology helps develop immersive interaction between real projects and stakeholders (e.g. clients, contractors, engineers), which makes online management more effective. In construction management field, AI brings a new direction for achieving convenient and efficient management of progress, safety, and quality in construction projects, especially for those that are on the remote sites. Under the support of blockchain and AI, automated contract execution can be achieved, including automated payment, real-time updates of referred government regulations, contract execution under unexpected weather, and etc. As more and more studies focus on this field, AI technology shows its vitality and broad prospects in the next generation collaboration.

However, existing platforms are still in its early stage and more studies are needed to make each required technique meet the requirements in the real-life construction projects. The large dataset for training is a common problem for the deep learning application in construction projects. In addition, the expensive computing costs and the low ability of generalization of the deep learning models requires future work to improve. The current AI-based As-planned BIM model generation methods cannot integrate schedule, which is the key to the progress monitoring. For as-built BIM model generation, there is a need for an end-to-end algorithm to efficiently achieve the production. Besides, As-built BIM model generation and progress management are both facing the challenge of occlusions and noise. The equipment and workers may block the construction elements behind them and they often move instead of being still. This situation reduces the accuracy of the system. Similar problems also occur in safety and quality management. Blockchain-based collaboration is still a framework, thus more work needs to be done. Localization is still a problem for AR, and it is difficult for current mobile devices to run AI algorithms to locate. For safety management and quality management, lacking effective datasets that have diverse data limits the performance, and it is hard to create a uniform dataset that suits all conditions. Besides, a widely accepted standard is required for the performance evaluation of detection. An effective alarming mechanism shall be established to reflect the detected results to related personnel. Finally, for AI in the AEC industry, the fragmentation of knowledge remains unresolved. A platform for integrating multiple technologies is still needed to achieve the "end-to-end" construction management.

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# TO DEVELOP AN INTELLIGENT INTEGRATED SUPPORT SYSTEM FOR ENGINEERING PROJECT (E-PMS): DECRIS AND DLDS ANALYSIS

**Jae Min. Cho[1], Sin Ae. Jang[2], Eul Bum. Lee[3] and Ju Hoon. Lee[4]**

**Abstract:** In order to manage engineering projects systematically and efficiently, the process of each project execution should be organically linked. The authors developed E-PMS (Engineering-Project Management System) for the linkage of processes. A tool called DECRIS (Detailed Engineering Completion Rating Index System) was developed to measure the completeness at the detailed design stage and to identify the starting point of construction (Steel Cutting). This helps the EPC contractor carry out the project by analysing the impact on schedules and costs during the engineering phase. Next is the DLDs Analysis. This study analysed the relationship between the results of the catch-up of the construction period and the delay liquidated damages (DLDs) based on limited resources and develops a model that can support the decision on whether to perform catch-up. The validity criterion of the model is that the results of the simulation of schedule shortening do not exceed the full DLDs incurred due to no catch-up plan. The result of the schedule catch-up simulation is the cost, which is the sum of the additional budget for a catch-up and the remaining DLDs. The reason for the validation criteria mentioned above is that the costs incurred for acceleration when excessive construction was performed to comply with the construction period can exceed the full DLDs.

**Keywords:** Project Management, EPC (Engineering, Procurement, Construction), Delay Liquidated Damages, Intelligent Project Management Information System, Construction Project Management System, Risk Management, Intelligent Decision-Making System.

## 1 INTRODUCTION

As the size and complexity of projects increased in the global plant market, management risks such as cost increase of project and delay in construction period increased from project order to completion. As a result, the improvement of management capability through decision support in each project phase is emerging as an important topic. Many advanced construction companies are building and using PMIS (Project Management Information System) for engineering-procurement-construction (EPC) project management to enhance the competitiveness and profitability of their engineering businesses. However, currently used PMIS is insufficient in extracting, storing, and standardizing raw data supporting key elements of project management such as process and cost. It is usually only a simple confirmation of performance compared to the

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progress rate calculation plan. Pre-emptive and proactive risk management capabilities are low. To manage engineering projects systematically and efficiently, processes by stages of project execution should be organically linked. In addition, to maximize the management efficiency of each process, raw data extraction, storage, and standardization techniques for risk management such as process and cost are required. Based on this data, an Engineering Project Life Cycle Management System should be established, and it is essential to develop a system that supports decision-making by providing decision criteria and data for each stage of execution. The study consists of <1> intelligent engineering integrated management frame-work, <2> element technology for integrated project management, <3> decision-making technology supporting integrated project management, <4> business owner LC response PMC technology, and, <5> integrated management system construction and verification. Among them, the authors developed a part of <3> decision-making technology that supports project management. The purpose of this paper is to introduce the Engineering Project Management System (E-PMS) developed through this research project briefly, especially two core modules related to E-PMS's decision-making technology and these are namely DECRIS and DLDs Analysis. The research was supported by the Ministry of Trade, Industry and Energy for 33 months and R & D was conducted to strengthen the competitiveness of the EPC project. This study was conducted by a consortium of three universities and four industries. USD 5.0M was supported by the Ministry of Trade, Industry and Energy.

## 2 Literature Review

As projects and their environments become more complex, there is a growing need for smarter systems that support decision-making and systematically manage project information as uncertainty, time and cost pressures. Accordingly, various research for the development of more intelligent PMIS have been conducted. [1] F.J.Jungen (1995) studied the framework for building an intelligent interactive project management support system. It presents a general framework for developing complex systems for tasks such as project management, dynamic scheduling, and design. [2] Ali Jaafari (1998) presents a new generation of PMIS called the Smart Project Management Information System (SPMIS), and the framework for SPMIS. [3] Paolo Donzelli (2006) studied the application of decision support systems for software project management. The hybrid modeling approach allows project managers to quickly generate process models that can provide accurate predictions, design desired project trajectories, and verify process changes. [4] Xiaoqing (Frank) Liu (2006) conducted a study of systems that help to assess the risks associated with three major problems of software projects: over budget, behind schedule, and poor quality. The system is based on fuzzy logic using an integrated set of software metrics. [5] Peter Smith (2016) studied the use of BIM to manage project costs. [6] Nathalie Labonnot (2017) demonstrated a design methodology that provides several frameworks for decision support systems related to the construction industry for more sustainable and intelligent construction. [7] Chang-Won Kim (2018) proposed an early-warning performance monitoring system (EPMS) to objectively measure and monitor project performance in order to detect inherent poor performance problems early. EPMS is built on project progress data and consists of a project information database, with an optimized theoretical model used as a performance metric, and an index for performance monitoring and prediction. As mentioned above, various studies have been conducted to improve the PMIS. However, in the above-mentioned previous studies, research on decision making models from the perspective of project management was absent during the whole phase of the EPC project field.

## 3 E-PMS(Engineering Project Management System)

E-PMS is a case-based Engineering Project Management System that supports optimal decision-making of engineering projects for each phase of the project. E-PMS can quickly and accurately identify the status of a project to be successfully completed in a timely manner, facilitate communication by sharing information among team members, unify data management, avoid duplicate work, and identify potential problems. It is a system for maximizing work efficiency through securing action time, standardizing work, and systemizing. E-PMS menu is divided into 'decision sup-port' and 'project management', and 'decision support' has two special modules, one is DECRIS, and the other is DLDs Analysis.

Table 1: E-PMS function overview

| Category | Module | Description |
| --- | --- | --- |
| Decision Support | Navigator | Project cost and construction period prediction and adequacy analysis by using DECRIS, ES-Chart, DLDs |
| | Dashboard | Project Status/Forecast/Risk & Forecast |
| Project Management | Project | Project Information Inquiry, Revision Management, Report Cycle Management, Site Location Inquiry Project Organization Information Inquiry, Project Image Inquiry, Supplier Inquiry Notice Board, Free Board, Individual / Project Schedule Management, Project Outcomes |
| | Contract | Contract Management, Statement Management, Bidding Process List |
| | Cost | Project budget execution plan inquiry, Project expense execution status inquiry, Actual Cost input |
| | Time | Management Standards Process Table Management, Contractor Process Table Setting and Management, Performance Chart Management Actual Progress Management, Milestone Schedule Management Process Status Inquiry, Master Schedule Inquiry, S-Curve Inquiry, Primavera Tool linkage, Linked log inquiry |
| | Quality | Submission management, official document sending and transmission management, Inspection document management, NCR document management |

| | |
|---|---|
| Risk | Risk Register Management by Report Cycle |
| Document | Project Document Management, Project Report Excel File Inquiry, Document Classification System Management, Document Form Management, Document Number Management, Electronic Payment Line Management |
| My Portal | Approval status, Scheduled / Starting Delay / Complete Delay Activity, Risk Identification, Recent NCR Issuance Status and My NCR Inquiry, Project Notice Inquiry |

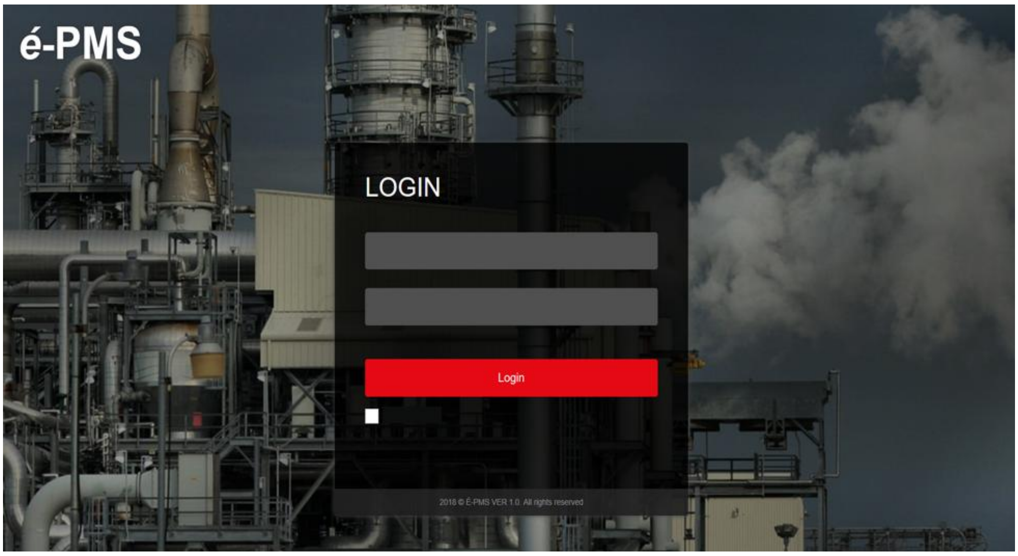



Fig. 1: Log-in window of E-PMS (Screen)

# 4 Decision-Making Module of E-PMS

## 4.1 DECRIS (Detail Engineering Completion Rating Index System) Model

The authors developed a DECRIS (Detail Engineering Completion Rating Index) system to calculate the engineering completion grade for offshore oil and gas EPC projects, using existing projects to validate their effectiveness. Because most construction schedules are tight, it is often necessary to begin construction before the design is complete. However, if the design is not finished, but the construction is started, there may be damages such as reconstruction due to the design change. Therefore, before design is complete, it is still necessary to know when it is okay to start (when damage is minimal). It is DECRIS that helps us know the point. The DECRIS methodology follows the PDRI approach, and The DECRIS model was developed in six steps:

1) DECRIS model range determination: Collect the preliminary elements from the existing literature and develop the element description

2) Data collection: Workshops were conducted with industry experts to determine which factors affect the calculation of detailed engineering completion grades and to organize the identified elements into appropriate sections and categories. Expert surveys were also used to collect data to calculate the relative importance of each element in the completion of engineering.

3) Data normalization: Determined weight factor using expert survey data, data normalization, preliminary estimation, verification process, average weight calculation of element, and interpolation.

4) Data analysis: One sample t-test was performed to complete the weight factor for each element. The weight factor of each element represents the level of factor contribution to the detailed engineering completion rating index.

5) Data application: The DECRIS model developed through the previous research stages have been validated by applying them to the 13 real projects case. Each project was evaluated using DECRIS level assessments.

6) Model verification: The score calculation results were compared with the project performance of each project using statistical analysis to confirm the level at which the model can predict project performance. A cutoff score was developed based on the model and sample project.

DECRIS is a model that predicts the increase of the construction period and construction cost based on the completeness of design. In other words, this model is developed based on the fact that the completeness of the design affects both procurement and construction. The lower the DECRIS score, the higher the completeness of the detailed design. In other words, an increase in the DECRIS score adversely affects the schedule and cost of the project. In this study, DECRIS is applied to past cases, and DECRIS acquisition scores are analyzed for each case at the main progress check point of the design. By comparing these scores with the delay level of the construction period in each case and the increase in the construction cost, a cutoff score is derived. The DECRIS cutoff scores derived from the major design progress phase were verified by regression analysis and t-test. In this study, after interviews with a practical expert with more than 15 years of plant design experience, authors have classified the design phase into 5 stages:

(1) FEED (Front-End-Engineering-Design) verification (Effective date)
(2) Equipment Procurement (30% modeling)
(3) AFD (Approved for Design) P & ID (60% modeling)
(4) AFC (Approved for Construction) P & ID (90% modeling)
(5) Design completion.

DECRIS was applied to the stages which are as follows; FEED verification, Equipment Procurement, AFD P & ID, AFC P & ID to verify the cutoff score and its usefulness.

The FEED verification step, the first step in reflecting design progress, is the time to review errors in the FEED provided by the client. At this stage, authors found that cost overrun and the schedule delay highly increased when DECRIS exceeded 865 points. If the score is higher than the 865, the cost and time are tripled than if it is lower than the score. In this study, the cutoff score was set to 865 and the usefulness was verified through regression analysis and t-test.

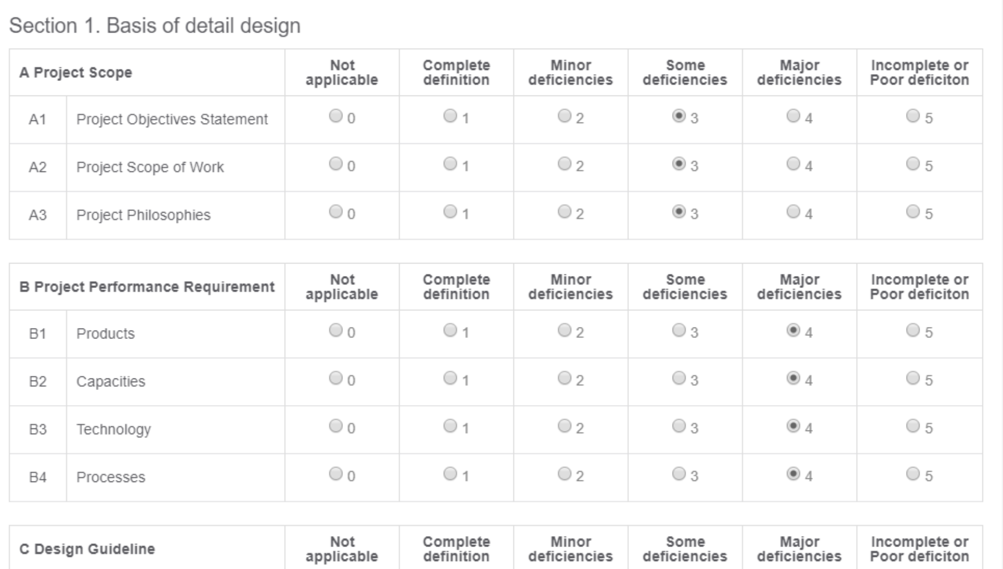
Equipment procurement step, the second phase of design progress, is generally the point of design review conducted in practice when modeling reaches 30%. In order to derive the cutoff score at this stage, the DECRIS scores of each case were analyzed and compared cost and schedule delay of each project. The case B project had a 17.14% increase in construction costs and a 411-day increase when the DECRIS score was 784. On the other hand, in the case I project, the construction cost increased by 2.84% when the DECRIS score was 674, and the construction period was delayed by 674 days. As a result, the construction period and the cost of construction increased sharply around the cutoff score 700. The authors compared increased costs and delays with higher and lower cutoff scores of 700. The difference was analyzed to be clear.

After doing the third AFD step in a similar way, the fourth and final result is: The fourth stage of reflecting design progress, the AFC P & ID step, is the stage of design completeness review conducted in practice when modeling reaches 90%. As a result of analyzing the increased cost and the delayed period according to the DECRIS score, in case B project, when the DECRIS score was 523, the construction cost increased by 17.14% and the construction period was delayed by 411 days. On the other hand, the case I project had a DECRIS score of 243 points, a 2.84% increase in construction costs, and an 82-day delay. The high DECRIS score group which has a high average score of 456, increased construction cost was 7.52%, and construction period was 229 days. On the other hand, in the case of a low DECRIS score group which has a low average score of 339, it increased by 2.19%, and 47 days. If the DECRIS score is above 380, construction costs and durations are significantly higher than below 380. (See Table 2)

Table 2: DECRIS Score of AFC P&ID step

| High DECRIS Score Group(Above 380) | | | | Low DECRIS Score Group(Below 380) | | | |
|---|---|---|---|---|---|---|---|
| Project | Score | Increased cost rate (%) | Construction period(day) | Project | Score | Increased cost rate (%) | Construction period(day) |
| G | 382 | 6.02 | 210 | I | 243 | 2.84 | 82 |
| D | 399 | 4.06 | 102 | K | 332 | 2.44 | 16 |
| X | 446 | 5.06 | 198 | C | 354 | 2.22 | -6 |
| H | 449 | 8.71 | 246 | L | 357 | 0.82 | 105 |
| F | 472 | 6.09 | 305 | E | 370 | 1.61 | 82 |
| A | 481 | 3.37 | 246 | J | 377 | 3.24 | 0 |
| M | 494 | 9.70 | 111 | | | | |
| B | 523 | 17.14 | 411 | | | | |
| Avg. | 456 | 7.52 | 229 | Avg. | 339 | 2.19 | 47 |

Regression analysis and T-verification were performed to statistically verify the effect of each DECRIS cutoff score on the cost performance and schedule performance of the four stages of design completion. As a result, each DECRIS cutoff score was found to have a statistically significant relationship. Each step is derived as above, and the user checks the matters step by step and grasps the influence of the process and cost by comparing the cutoff score and the derived values.



Section 1. Basis of detail design

| A Project Scope | | Not applicable | Complete definition | Minor deficiencies | Some deficiencies | Major deficiencies | Incomplete or Poor deficiton |
|---|---|---|---|---|---|---|---|
| A1 | Project Objectives Statement | ○ 0 | ○ 1 | ○ 2 | ◉ 3 | ○ 4 | ○ 5 |
| A2 | Project Scope of Work | ○ 0 | ○ 1 | ○ 2 | ◉ 3 | ○ 4 | ○ 5 |
| A3 | Project Philosophies | ○ 0 | ○ 1 | ○ 2 | ◉ 3 | ○ 4 | ○ 5 |

| B Project Performance Requirement | | Not applicable | Complete definition | Minor deficiencies | Some deficiencies | Major deficiencies | Incomplete or Poor deficiton |
|---|---|---|---|---|---|---|---|
| B1 | Products | ○ 0 | ○ 1 | ○ 2 | ○ 3 | ◉ 4 | ○ 5 |
| B2 | Capacities | ○ 0 | ○ 1 | ○ 2 | ○ 3 | ◉ 4 | ○ 5 |
| B3 | Technology | ○ 0 | ○ 1 | ○ 2 | ○ 3 | ◉ 4 | ○ 5 |
| B4 | Processes | ○ 0 | ○ 1 | ○ 2 | ○ 3 | ◉ 4 | ○ 5 |

| C Design Guideline | Not applicable | Complete definition | Minor deficiencies | Some deficiencies | Major deficiencies | Incomplete or Poor deficiton |
|---|---|---|---|---|---|---|

Fig. 2: DECRIS Check List: FEED verification (Effective Date) of E-PMS (Screen)

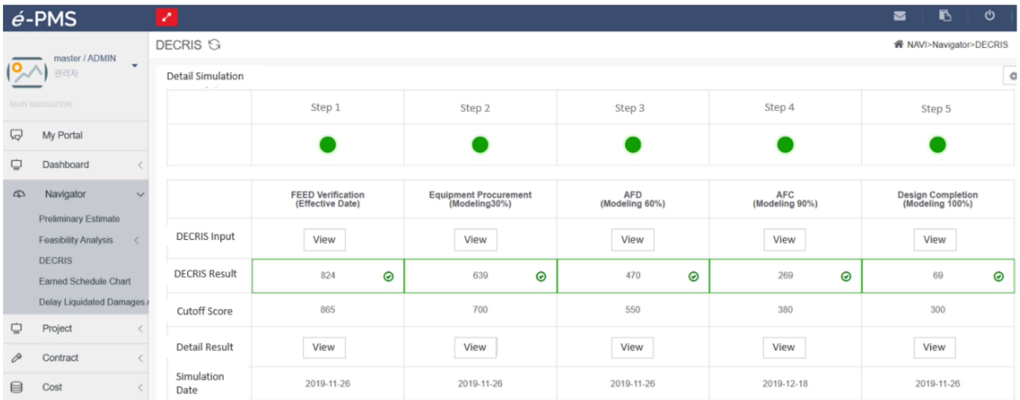



Fig. 3: DECRIS Execution Result of E-PMS (Screen)

## 4.2 DLDs Analysis Model

This study analyzes the relationship between the results of the catch-up of the construction period and the delay liquidated damages (DLDs) based on limited resources and develops a model that can support the decision on whether to perform catch-up. The validity criterion of the model is that the results of the simulation of schedule shortening do not exceed the full DLDs incurred due to no catch-up plan. The result of the schedule catch-up simulation is the cost, which is the sum of the additional budget for catch-up and the remaining DLDs. The reason for the validation criteria mentioned above is that the costs incurred for acceleration when excessive construction was performed to comply with the construction period can exceed the full DLDs. To solve this, the model was developed in three stages. First, the model was developed to predict the delay of the construction schedule with high accuracy. Existing EPC companies have used EVMS (Earned Value Management System) to determine their performance against plans. In other words, it analyzed whether construction was delayed. However, there is a cutoff in terms of accuracy in predicting time schedules in EVMS, which is a cost unit. To overcome this problem, the author applied the Earned Schedule (ES) algorithm, developed by Lipke in 2003 to improve the accuracy of the construction delay prediction when analyzing DLDs. Second, according to the number of critical paths in the construction stage, an appropriate option model is provided to derive shortened simulation results based on limited resources. Third, decision support information is provided through an analysis of the relationship be-tween schedule shortening results and full DLDs. In the second step, the Option Mod-el selection can be divided into <Option 1> and <Option 2>, depending on the case of 1 and n (≥2) critical paths. The criterion for the major classification between the two option models is the number of critical paths, and the detailed differences appear in the process of applying the shortening algorithm. In this case study, to verify the developed model, a scenario was constructed based on the data from the Vietnam Construction Project of P Company and the EPC Power Project provided by H Company (Construction Management). The scenario consisted of a 72-day delay in construction, ▲ DLDs (50,000/Day), ▲No Grace Period & Concurrent Period, and ▲an available budget (USD 250,000). As a result, Option Model 1 accelerated 12 days in construction delay and saved USD 450,137 of its Full DLDs (USD 3,600,000). In the case of Option Model 2, the scenario saved 10 days and reduced USD 746,398 of the Full DLDs. Both Option Models meet the model validity criteria. In an EPC project, project managers (user) can predict delays in construction and check the information on activities to catch-up, whether to shorten it in order to meet the completion due date or more economical to pay the full amount of DLDs during construction. Thus, timely information can be provided to the project managers.

The DLDs Mitigation Model runs on cut-off dates. First, through ES-EVMS, the construction delay is predicted. At this time, if the construction schedule is ahead of schedule (Ahead of Schedule) or the same time (On time), the construction may be performed according to the schedule. However, if is behind schedule, move on to analysis through the DLDs Mitigation Model. Second, in the step of utilizing (analyzing) the DLDs Mitigation Model, the detailed Option Model is selected according to the number of <Critical Path>. If there is one critical path, select Option Model 1; if n, select Option Model 2. Here, n means two or more. Third, after the Option Model is selected, the number of problems that may occur in the simulation process may be n at CP = 1. This is because, when shortened, near CP has the same construction period as shortened main process (CP). Near CP means that the construction period is shorter than the main process, but the difference in the main process is within 30 days. During the simulation of Option Model 1, if there are multiple CPs, the simulation stops. And based on the relevant process data, through Option Model 2, it is a principle to shorten. Thus, Near CP was generated to overcome the problem. So, in Fig. 4, Option Models 1 and 2 are connected by dotted lines to indicate the possibility of the intersection. The results analyzed in this way are compared in two ways. Comparison targets include: △ DLDs (per day) and △ average daily reduction costs. And if the DLDs (per day) is small, it supports decision making by paying the delayed amount as much as it is delayed without performing a reduction. However, if the DLDs (per day) is large, it shorten executions to support decision making by mitigating the late compensation costs due to the delay.

Fourth, in case of delayed compensation due to failure to shorten, support for decision making is secured by credit loss provisions. The provision for bad debts is to anticipate losses and accumulate damages in accounting accounts.

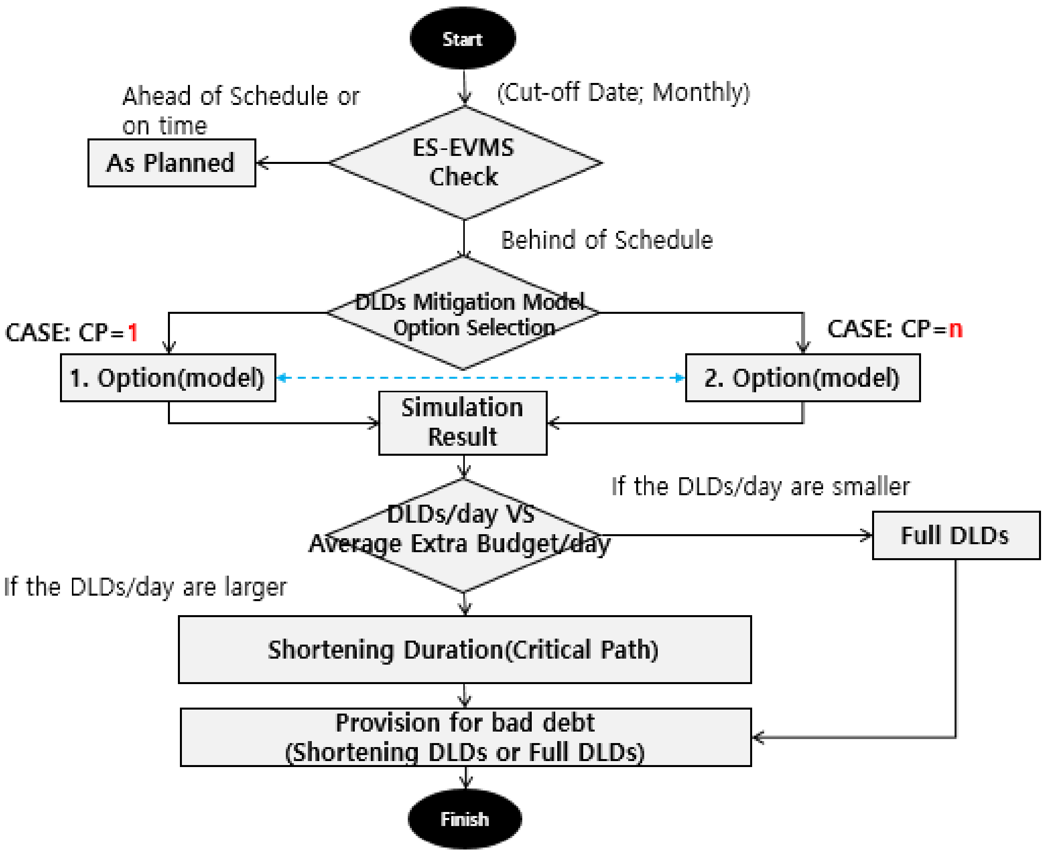



Fig. 4: DLDs Mitigation Model (Integration)

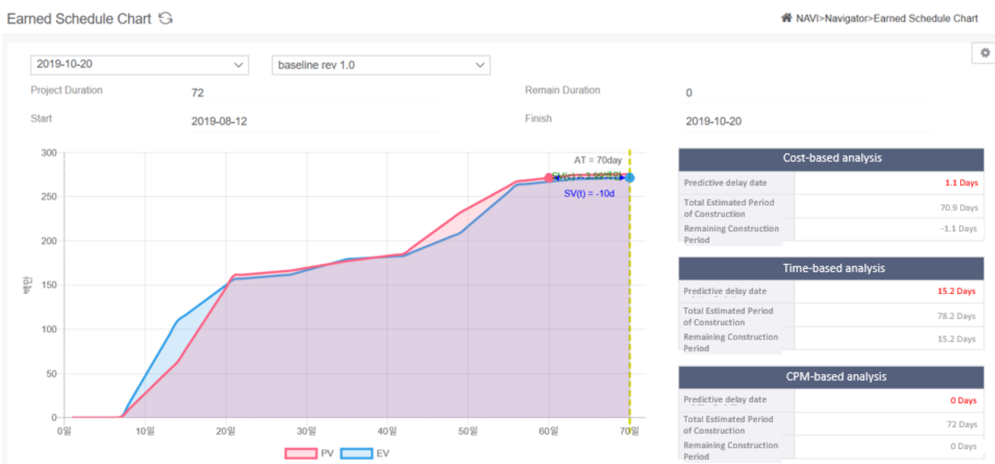



Fig. 5: Earned Schedule Chart of E-PMS (Screen)

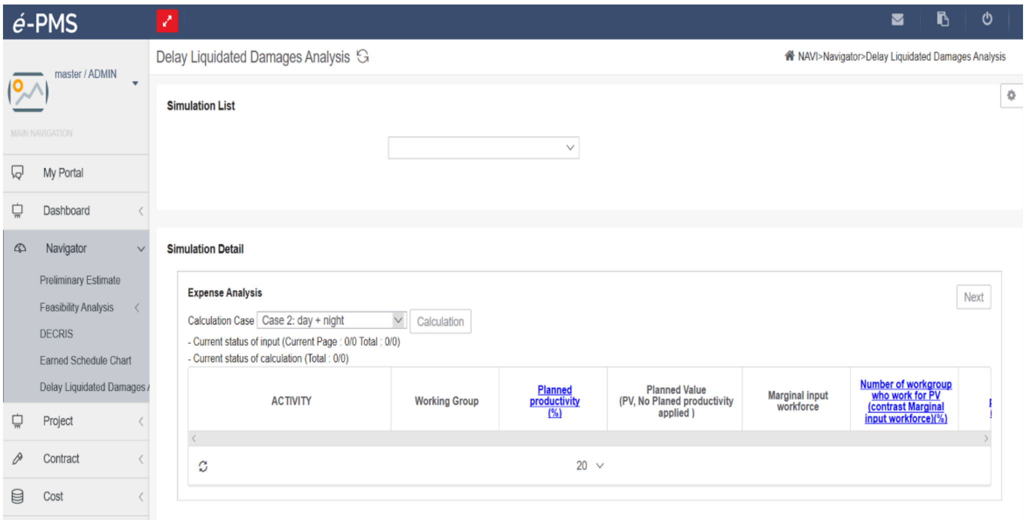



Fig. 6: Delay Liquidated Damages Analysis of E-PMS (Screen)

## 5 Conclusions

In this study, the authors developed E-PMS, an intelligent PMIS that includes decision support functions (DECRIS and DLDs Analysis). E-PMS not only manages and monitors information on all stages related to the project, but also enables optimal decision making through DECRIS and DLDs Analysis. Intelligent PMIS goes beyond the limits of what it does. With DECRIS, when the detailed design is not complete, it is possible to determine the appropriate starting point for construction based on the completeness of the design. The DECRIS model can contribute to the project success on the construction execution stage by forecasting project performance and potentially reducing the project underperformance risks. The on-time delivery within budget for offshore oil and gas EPC projects using the DECRIS model will also give a positive motivation for major oil companies who place a great deal of attention on project success. Another decision support model, DLDs Analysis (Delay Liquidated Damages, DLDs Analysis), is a model that allows additional resources to be shortened or delayed if the construction period is delayed. Decision support through DECRIS and DLDs Analysis can help EPC contractors complete successful projects by minimizing cost loss and minimizing risk.

## 6 Limitation and Future Works

Historical data from the current DECRIS model is based on the results of the EPC project of large offshore projects in Korea. It is not established that the DECRIS model can be applied to other industries or other countries with a different company organization or project characteristics. DECRIS models can be further improved and developed for various project types through further research. The DLDs Mitigation Model has a lot of initial input values and it should be easy to collect all relevant information. In fact, the field team spends a lot of time managing milestones such as Primavera 6. Given these field conditions, the limitations of the model should be enhanced automation and connectivity. The EPC contract also recommends that process control utilize commercially available tools. One of the main tools is Primavera 6, which should be linked. In terms of usability, if the initial construction plan and the revised construction plan are mutually reflected, it will be supplemented in the above-mentioned automation.

## 7 Acknowledgement

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# DEVELOPMENT OF AI-BASED ENGINEERING BIG DATA INTEGRATED ANALYSIS SYSTEM FOR DECISION-MAKING SUPPORT IN THE ENGINEERING-PROCUREMENT-CONSTRUCTION (EPC) INDUSTRY

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**Abstract:** Plant Engineering-Procurement-Construction (EPC) industry is one of the complex industries going through various stages from bidding to engineering, construction and operation and maintenance (O&M). A systematic management system is needed to address these complexities. However, many EPC companies in Korea are having difficulty managing their projects due to the lack of data-based systematic decision-making, and are suffering heavy losses in overseas projects.

The AI-based engineering big data integrated analysis system proposed by this study aims to minimize project losses and eventually to enhance the technical skills and competitiveness of the Korean plant industry through decision-making support, combining big data and AI in the entire EPC project life cycle. In this study, knowledge base was established to utilize various data generated during the entire EPC project life cycle in AI-based engineering big data integrated analysis systems. And a machine learning integrated platform specialized in the engineering industry was developed to support feature engineering, model learning and model operation processes. Using various algorithms from the machine learning integration platform and the knowledge base, five main decision-making applications were developed: analyzing bidding documents, predicting design costs, analyzing design errors, analyzing change order, and plant equipment prediction maintenance.

Based on the predicted information, the system could help EPC project managers identify and manage risks at each stage of the project in advance to make decisions that minimize project loss. Furthermore, the information predicted at each stage may be circulated or used as feedback for decision making at other stages.

**Keywords:** Plant Project, Engineering, Construction Lifecycle, Smart Decision-making support system, Big-Data, Artificial Intelligence.

## 1 INTRODUCTION

The plant industry is made up of large, complex industries having various phases, ranging from bidding to engineering, construction, operation and maintenance, as well

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as high-tech manufacturing technologies, and technology-intensive industries that require knowledge services such as design, production and finance.

However, many EPC companies are having difficulties in Life-cycle construction management because they do not have a data-based, systematic decision-making system such as a track record. In addition, insufficient management of unknown risks such as Country Risk and Schedule Risk often results in losses in construction.

In addition, in order for Korean EPC companies to survive the competition with major global EPC companies, it is imperative to secure competitiveness against plant value chains, including high value upstream parts such as Project Management Consultancy (PMC) and Front-End Engineering Design (FEED).

Therefore, in order to lay the foundation for securing the competitiveness of the Korean plant industry, we suggest AI-based engineering big data integrated analysis system technology that enables optimal decision making and execution in the pre-plant cycle process so that Korean EPC companies could predict and respond to risks in the bidding, execution, construction and maintenance phases of the project in advance.

To support decision-making by project stage, the research team built a knowledge base ranging from ITB (Invitation to Bid, bid document) analysis at the bidding stage to plant facility forecast maintenance of the O&M stage, select-ed features, and combined algorithms of machine learning platforms to create a machine learning solution.

The following Table 1 shows the five modules of this engineering decision-making technology development.

Table 1: Summary of five study parts.

| Project Stage | Module | Contents |
|---|---|---|
| Bidding | Engineering design cost prediction | Analysing past engineering design man-hour and cost to predict accurate engineering design man-hour of new project |
| Bidding | Engineering ITB analysis | Establish bidding strategy through analysis of con-tract key issues and respond to risks through analysis of risk clause |
| Engineering | Engineering Design Error Analysis | Analysis of design error report (crash, missing report) information to provide proactive design risks and types of equipment and equipment with high potential for design delay and error |
| Engineering &Construction | Engineering Change Order Analysis | Analyse the causes of design changes and pre-sent risk impact and trend by types, and provide information that can be reflected in contract, design, purchase, and construction work. |
| Operation &Maintenance | Plant Equipment Predictive Maintenance | Predict maintenance items for major plant facilities |

In addition to introducing the above five key decision support modules in Section 3, this Paper will cover one of the decision support modules in Section 4 in more detail.

# 2 LITERATURE REVIEW

In recent years, the construction industry has become more complex, and the need for advanced project management is increasing. As a result, there are a growing number of cases and studies that apply big data, AI, and machine learning algorithms to the construction industry. [1] James. D(2005) of AACE present-ed a correlation and prediction study between equipment and plant engineering design man-hours using regression analysis. [2] Mohamed Marzouk(2016) developed a water treatment plant construction estimating model using the Artificial Neutral Network Method in 2016. [3]Sphurti S. Arage (2017) and [4] Igor Pesko (2017) developed a Civil Construction Cost Estimation model by applying machine learning algorithms in their respective studies.

However, compared to other industries, the plant industry is relatively slow in applying machine learning and quantitative statistical analysis. In particular, researches for predicting plant engineering design man-hours are not actively con-ducted, and each EPC company or Engineering company adheres to the tradition-al method of estimating and calculating quantities. Therefore, this study intends to present engineering design man-hour prediction model after collecting historical data and performing quantitative analysis.

# 3 FIVE DECISION SUPPORT MODULES INTRODUCTION

As mentioned above, this study consists of five modules, such as engineering design cost prediction, engineering design error analysis, engineering design change analysis, engineering ITB analysis, and plant facility forecasting maintenance, and this section provides a summary of the objectives and development methods of these five modules.

## 3.1 Engineering Design Cost Prediction

Estimating design costs is the work performed in the initial bidding phase of the project and has a great impact on the decision making of the project participants. EPC Company or Engineering Company shall estimate accurate design costs and reflect them in the schedule and expense plan before embarking on plant design work. However, since there is limited information available at the beginning of the project, qualitative factors such as the experience of the engineers in charge are often reflected, and hence the accuracy of the estimate has been often less accurate. Thus, this research team collected about 40 past EPC plant project data consisting of drawing list, equipment list and project information, etc. and con-ducted analysis from a big data perspective. As a result, a model was developed to estimate the engineering design man-hour using information from the beginning of the project, and a function was implemented to select and provide useful reference data to project participants.

## 3.2 Engineering Design Error Analysis

In plant projects, where a large amount of complex design is executed in a short period of time, design errors and omissions often occur. These design errors and omissions are one of the main risk factors that cause schedule delay, cost in-creases, and quality degradation during the subsequent construction phase, and not just during the design phase. Therefore, in this module after collecting historical plant project data, we developed an automatic classification system of design errors and an algorithm to predict the risks from the cost aspects of each type in order to minimize a project risk due to design errors by utilizing big data statistical analysis and machine learning.

### 3.3 Engineering Change Order Analysis

Due to the nature of long-running plant projects, design changes are often caused by internal causes of the project, such as scope, function and use, and by external factors such as political, economic and environmental changes. However, it is not uncommon for compensation from owners for delays and increases in costs caused by design changes to be paid improperly. And this leads to a loss to project participants. Therefore, this module developed a design change type automatic classification system and severity prediction algorithm by classifying de-sign changes by type and calculating the severity by type based on historical data so that users can proactively recognize and cope with the risks of design changes occurring.

### 3.4 Engineering ITB Analysis

The bidding phase of a plant project is a very important period for project participants. Early detection of potential risk conditions on bid documents and prevention of losses is a prerequisite for successful project execution within a limited period of time, and is generally required by a large number of experts in each field. In this module, the NLP(Natural Language Process) and text-mining technology, and machine learning are used to prepare systematic procedures for the extraction of risk clauses on bid documents, and to automate tasks to enable more objective and quick review of bid documents.

### 3.5 Plant Equipment Predictive Maintenance

Ensuring the stability of plant facility system operation is of paramount importance to prevent major accidents. Although preventive maintenance and parts replacement are carried out regularly to prevent the failure of the facility system, such existing methods are limited in preventing the sudden failure. Therefore, to minimize the loss of plant operators, this study developed a technique for predicting equipment failure by using anomaly detection and machine learning techniques. By using the developed prediction algorithm, accurate pre-diagnosis can reduce unnecessary maintenance costs, increase the stability and reliability of the system, and prevent system failures and accidents.

## 4 ENGINEERING DESIGN COST PREDICTION

This section dwells on the design cost prediction module, one of the five modules introduced above. The purpose of this study is to identify the correlation between information (Basic Drawing list, Equipment list, Line list, etc.) that can be used in the initial bidding stage of a project and actual design man-hour, and to create a prediction model.

The collected drawing list was reclassified into 27 design activities using SMEs, and Unit man-hour was calculated for each activity. Then, the design man-hour trend was analysed according to the project country, duration, and scale. User can calculate the general design man-hour by inputting the required quantity based on the 27 design activity lists. The developed correction factor can be used to increase the accuracy of the estimate according to the characteristics of the user project. In addition, a similar project recommendation function using the CBR technique was implemented. The step-by-step flow is summarized in Figure 1 below, and each of these steps is described in detail in the following sections.

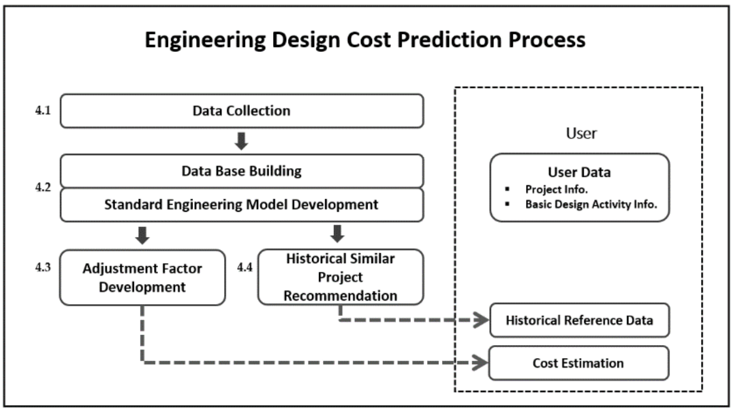


Fig. 1: Engineering design man-hour prediction algorithm development flow

## 4.1 Data Collection

Many historical plant project data have been collected.

This section introduces historical plant project data collected from project participants. In particular, this study focused on collecting and analysing data related to piping design, which takes up 40-50% man-hour of the plant's overall design work volume and 25-34% of the total construction cost of the plant. Data from 40 projects comprising drawing list, equipment list, and project information were collected.(Figure 2,3 below).

| A Project | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 공종 | WBS | Drawing | | Category | WBS Manhour | Completion Percentage of Stage(Plan) | | | | | |
| | WBSCODE | DWG No. | DWG Title | | | Step 1 | Step 2 | Step 3 | Step 4 | Step 5 | Step 6 |
| | | | | | | START (0%) | STUDY (5%) | DRAFT (10%) | IFR (30%) | IFC (55%) | |
| PR | A0EA0PR0020501 | U00-K-0021-RP | WASTE DISPOSAL REPORT | A | 71 | 2012-11-01 | 2012-11-06 | 2012-12-24 | 2012-12-31 | 2013-02-28 | 2013-04-16 |
| | | | | | | START (0%) | STUDY (5%) | DRAFT (10%) | IFR (10%) | IFD (15%) | AFD (10%) |
| PR | A0EA0PR0020601 | U00-K-0026-SA | OPERATING WINDOWS AND SAFE OPERATING ENVELOPS | A | 72 | 2012-11-30 | 2012-12-05 | 2013-10-04 | 2013-10-22 | 2013-12-20 | 2014-01-31 |
| | | | | | | START (0%) | STUDY (5%) | DRAFT (10%) | IFR (30%) | IFC (55%) | |
| PR | A0EA0PR0020801 | A0EA0PR0020801 | OPTIMIZATION STUDIES & EVALUATION REPORT | R | 70 | 2013-08-01 | 2013-08-15 | 2013-10-31 | 2013-11-15 | 2014-01-16 | |
| | | | | | | START (0%) | IFI (100%) | | | | |
| PR | A0EA0PR0020901 | U00-K-0025-PR | VENDOR INFORMATION ON PACKAGE UNITS | I | 67 | 2013-07-01 | 2013-09-30 | | | | |
| | | | | | | START (0%) | STUDY (5%) | DRAFT (10%) | IFR (30%) | IFC (55%) | |
| PR | A0EA0PR0021001 | U00-K-0023-PD | ALARM & TRIP VALUES | R | 374 | 2013-07-01 | 2013-07-09 | 2013-09-25 | 2013-10-07 | 2013-12-31 | |
| | | | | | | START (0%) | STUDY (5%) | DRAFT (10%) | IFR (30%) | IFC (55%) | |
| PR | A0EA0PR0021101 | U00-K-0019-PR | CATALYST AND CHEMICALS HANDLING AND LOADING PROCEDURES | R | 70 | 2013-09-02 | 2013-09-11 | 2013-12-18 | 2013-12-31 | 2014-02-20 | |

Fig. 2: Drawing List Sample

**INFORMATION & VENDOR PRINT STATUS**

| UNIT | ITEM NO. 1 | ITEM NO. 2 | | | DESCRIPTION | EQUIPMENT TYPE | QTY | DATASHEET | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | REV. | RECEIVED | DIMENSION FOR NOZZLE | |
| | | | | | | | | | | YES | NO |
| Unit A | C-74101 | C | 74101 | | RECYCLE COMPRESSOR | COMPRESSOR | 1 | B0 | 2008.01.30 | | O |
| Unit A | C-74102A/B | C | 74102 | A/B | MAKE-UP COMPRESSOR | COMPRESSOR | 2 | B1 | 2009.06.01 | | O |
| Unit A | C-74201 | C | 74201 | | RECYCLE COMPRESSOR | COMPRESSOR | 1 | B0 | 2008.01.30 | | O |
| Unit A | C-74202 | C | 74202 | | MAKE-UP COMPRESSOR | COMPRESSOR | 1 | B1 | 2009.06.01 | | O |
| Unit A | C-74401 | C | 74401 | | RECIRCULATION COMPRESSOR | COMPRESSOR | 1 | B1 | 2009.06.01 | | O |
| Unit A | DS-74301 | DS | 74301 | | MP STEAM DESUPERHEATER | MISCELLANEOUS | 1 | B1 | 2010.01.22 | | O |
| Unit A | DS-74302 | DS | 74302 | | STRIPPER DESUPREHEATER | MISCELLANEOUS | 1 | B1 | 2010.01.22 | | O |
| Unit A | DS-74303 | DS | 74303 | | LP STEAM DESUPERHEATER | MISCELLANEOUS | 1 | B1 | 2010.01.22 | | O |

Fig. 3: Equipment List Sample

## 4.2 Standard Master Drawing Register for piping development and data standardization

### 4.2.1 Standard Master Drawing Register (SMDR)

Standard Master Drawing Register (SMDR) was developed and the collected data was standardized.

Drawing lists of the collected projects were reorganized to the same standards in collaboration with plant engineers with more than 20 years of experience. And database was built (Table 2 below). Based on the unit man-hours of drawing list of each project, the average value for each of the 27 standardized design activities was calculated as the standard unit man-hour. Table 2 below shows 27 design activity lists and unit man-hours.

Table 2: SMDR (Standard Master Drawing Register)

| No. | Design Activity List | Unit Man-hour(hours) |
|---|---|---|
| 1 | Line list & Tie in List | 123 |
| 2 | Piping Information drawing | 215 |
| 3 | Vendor Print Review & Data sheet | 499 |
| 4 | UFD & PNID Review | 91 |
| 5 | Plot Plan & Equipment Arrangement drawing | 91 |
| 6 | Utility Station & Safety Shower Location Plan | 18 |
| 7 | Steam Tracing Diagram | 28 |
| 8 | Tracing Circuit drawing | 4 |
| 9 | Stress Geometry drawing | 4 |
| 10 | Pulsation Study Diagram | 45 |
| 11 | B/M Sketch drawing & MTO with key Punch | 2 |
| 12 | Key plan drawing. | 17 |
| 13 | Standard & Special Support Detail drawing | 4 |
| 14 | Stress Geometry drawing | 4 |
| 15 | Stress analysis_Specialty item data sheet for stress | 5 |
| 16 | Stress analysis_Piping Flexibility analysis_Critical | 239 |
| 17 | Stress analysis_Piping Flexibility analysis_Non Critical | 162 |
| 18 | Stress analysis_AIV&FIV analysis & report | 97 |
| 19 | Conceptual Piping Design_Process Area | 76 |
| 20 | Conceptual Piping Design_P/R & Off site area | 60 |
| 21 | Conceptual Piping Design_U/G area | 23 |
| 22 | PDMS Modeling(Equipment) | 55 |
| 23 | PDMS Modeling(Layout) | 207 |

| | | |
|---|---|---|
| 24 | PDMS Model Review | 80 |
| 25 | ISO drawing & BM Generation | 2 |
| 26 | 3D Piping plan drawing Generation | 13 |
| 27 | Piping Engineering follow up(INCL. AS Built) | 450 |

### 4.2.2 Data Standardization

The collected data was standardized in the same form.

For the convenience of comparison and analysis, all project data were converted as follows. The period was calculated on a monthly basis and the project areas were classified into Korea, Middle East Asia, and Southeast Asia. Project scales (project cost) were converted to Dollar in 2019 using the CPI(Consumer Price Index). In the case of the equipment list, information on the quantity of equipment considered to affect the design time was calculated. The Fig 4 below show the standardized data set form.

**Plant Engineering Project Database**

| Project Number | 1 | 2 | 3 |
|---|---|---|---|
| Project Name | Project A | Project B | Project C |
| Onshore / Off shore | Onshore | Onshore | Onshore |
| Plant Type | refinery | refinery | Chemical |
| Contractor | D EPC Company | D EPC Company | D EPC Company |
| Owner | S Owner Company | E Owner Company | E Owner Company |
| Country | Korea | Middle East Asia (Iran) | Middle East Asia (Iran) |
| Project Duration (Months) | 27 | 38 | 16 |
| Project Scale (Dollar) | 20768120 | 15175656 | 5901919 |
| Equipment Quantity | 163 | 63 | 21 |
| Piping Line Quantity | 11110 | 666 | 473 |

| No. | Standard Drawing List for Piping | Unit MH | Q'ty | Total MH | Unit MH | Q'ty | Total MH | Unit MH | Q'ty | Total MH |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Line list & Tie in List | 168 | 1 | 168 | 55 | 1 | 55 | 23 | 1 | 23 |
| 2 | Piping Information drawing | 337 | 1 | 337 | 109 | 1 | 109 | 45 | 1 | 45 |
| 3 | Vendor Print Review & Comments | 1,010 | 1 | 1,010 | 328 | 1 | 328 | 136 | 1 | 136 |
| 4 | UFD & PNID Review | 100 | 1 | 100 | 100 | 1 | 100 | 100 | 1 | 100 |
| 5 | Plot Plan & Equipment Arrg't drawing | 95 | 7 | 665 | 95 | 2 | 190 | 95 | 2 | 190 |
| 6 | Utility Station & Safety Shower Loaction Plan | 20 | 3 | 50 | 19 | 2 | 38 | 19 | 1 | 19 |
| 7 | Steam Tracing Diagram | 30 | 2 | 50 | 29 | 1 | 29 | 29 | 1 | 29 |
| 8 | Tracing Curcuit Drawing | 2 | 90 | 180 | 2 | 91 | 181 | 2 | 220 | 524 |
| 9 | Stress Geometry drawing | 4 | 280 | 1,067 | 4 | 420 | 1,596 | 4 | 220 | 836 |
| 10 | Pulsation Study Diagram | 40 | 23 | 900 | 48 | 20 | 950 | 48 | 20 | 950 |
| 11 | B/M Sketch dwg. & MTO with key Punch | 1 | 4,500 | 5,130 | 1 | 2,000 | 2,000 | 1 | 225 | 257 |
| 12 | Key plan dwg.(2D New & Exist) | 40 | 1 | 40 | 10 | 1 | 10 | 10 | 1 | 10 |
| 13 | Standard & Special Support Detail drawing | 4 | 30 | 120 | 4 | 30 | 120 | 4 | 30 | 120 |
| 14 | Stress Geometry drawing | 4 | 300 | 1,200 | 4 | 300 | 1,200 | 4 | 300 | 1,200 |
| 15 | Stress analysis _ Specialty item data sheet for stress | 4 | 35 | 140 | 5 | 30 | 143 | 5 | 30 | 143 |
| 16 | Stress analysis_ Piping Flexbility analysis_Critical | 23 | 210 | 4,828 | 20 | 225 | 4,500 | 20 | 225 | 4,500 |
| 17 | Stress analysis_ Piping Flexbility analysis_Non Critical | 19 | 185 | 3,480 | 15 | 200 | 3,000 | 15 | 200 | 3,000 |
| 18 | Strss analysis_AIV&FIV anaysis & report | 100 | 1 | 100 | 100 | 1 | 100 | 100 | 1 | 100 |
| 19 | Conceptual Piping Design_Preocess Area | 81 | 35 | 2,826 | 81 | 6 | 485 | 81 | 2 | 162 |
| 20 | Conceptual Piping Design_P/R & Off site area | 52 | 25 | 1,306 | 52 | 3 | 157 | 52 | 1 | 52 |
| 21 | Conceptual Piping Design_U/G area | 24 | 1 | 24 | 24 | 1 | 24 | 24 | 1 | 24 |
| 22 | PDMS Modeling(Equipment) | 42 | 19 | 820 | 36 | 1 | 36 | 35 | 1 | 35 |
| 23 | PDMS Modeling(Layout) | | | | | | | | | |
| 24 | PDMS Model Review | 25 | 257 | 6,347 | 214 | 29 | 6,195 | 215 | 6 | 1,290 |
| 25 | ISO Dwg. & BM Generation | 150 | 1 | 150 | 150 | 1 | 150 | 150 | 1 | 150 |
| 26 | 3D Piping plan drawing Geneation | 250 | 1 | 250 | 250 | 1 | 250 | 250 | 1 | 250 |
| 27 | Piping Engineering follow up(INCL. AS Built) | 400 | 1 | 400 | 400 | 1 | 400 | 400 | 1 | 400 |
| | Total | 3,025 | 10 | 31,688 | 2,154 | 10 | 22,345 | 1,866 | 8 | 14,543 |

Fig. 4: Standardized data set example

## 4.3 Adjustment Factor Development

Adjustment factors were developed to reflect trends in design man-hour according to project characteristic information. After setting the project characteristic classification criteria (Table 3) through the SME(Subject Matter Expert)s survey technique, the factor was calculated by comparing relative increments and reductions.

Currently, the country factor, period factor, and scale factor have been developed, and detailed development methods are as follow. User can apply by multiplying each factor according to the user's project condition by the standard de-sign man hour value calculated using the SMDR of 4.2section

Table 3: Project Characteristic Classification Criteria

| Adjustment Factors | Classification | |
|---|---|---|
| Country | Korea (Standard) | Korea |
| | Middle East Asia | Malaysia |
| | Southeast Asia | Saudi Arabia<br>Iran |
| Duration | 0 - 12 months | |
| | 13 - 24 months (Standard) | |
| | 25 - 36 months | |
| | 37 - 48 months | |
| Scale | Less than $1 million | |
| | More than $1 million and less than $4 million (Standard) | |
| | More than $4 million and less than $6 million | |
| | More than $6 million | |

### 4.3.1 Country Factor

The country factor was developed to reflect the design man-hour change by country condition. An engineering man-hour prediction regression model was developed for 20 projects conducted in Korea. After that, the characteristic information variables of other country project were inputted into the Korean project regression prediction model, and the increase/decrease rate was regarded as a difference according to the country of the project. The regression model for Korea Project results and developed factors are shown in Table 4 below.

Table 4: Summary of Korea Project Regression Model and Country Factor

| Regression Model for Korea Project | | | Country Factor | | |
|---|---|---|---|---|---|
| MAPE(%) | R-squared | P-value | Korea | Middle East Asia | Southeast Asia |
| 11.41 | 0.94 | $1.042 \times 10^{-8}$ | 1.0 | 1.20 | 0.83 |

### 4.3.2 Duration Factor

Similar to the above method, we created a regression model that predicts man-hours for projects ranging from 13 to 24 months. And design man-hour was predicted by inputting variables of different period groups. Like the Country Factor, the difference between the predicted and actual values was considered to be due to the duration of the project. The regression result and developed factors are summarized in the table5 below.

Table 5: Summary of Normal Duration Project Regression Model and Duration Factor

| **Regression Model Normal Duration Project** | | | **Duration Factor** | | | |
|---|---|---|---|---|---|---|
| MAPE(%) | R-squared | P-value | 0-12 months | 13-24 months | 25-36 months | 37-48 months |
| 19.40 | 0.87 | $2.867 \times 10^{-5}$ | 0.93 | 1.0 | 1.13 | 1.35 |

### 4.3.3 Scale Factor

Scale factors have also been developed similar to the above method. After generating a man-hour prediction regression model with a project of the general scale, the design man-hour was estimated using small-scale and large-scale data as in-put variables. The difference between the design man-hour value and the actual value of the two project scale groups predicted by the model was considered to be due to the tendency to follow the group. The regression model result and developed factors are shown in Table6 below.

Table 6: Summary of Normal Scale Project Regression Model and Scale Factor

| **Regression Model for Normal Scale Project** | | | **Scale Factor** | | | |
|---|---|---|---|---|---|---|
| MAPE(%) | R-squared | P-value | Less than $ 1 million | More than $ 1 million and less than $ 4 million | More than $ 4 million and less than $ 6 million | More than $ 6 million |
| 12.87 | 0.90 | $7.189 \times 10^{-6}$ | 0.83 | 1.20 | 1.17 | 1.37 |

## 4.4 Historical Similar Project Recommendation

In addition, similar project suggestion function using CBR method has been developed. CBR method is a technique that finds the most similar cases among past cases and uses that for problem solving. In this study, the priority of each factor in judging project similarity was investigated through SME questionnaire. These factors refer to the standardized project data set introduced in section 4.2. The survey results of SME were used to establish similar project selection criteria and the criteria in-formation is shown in Table 7 below.

Table 7: Similar Project Selection Criteria and Survey Result

| SME | Result #1 | Result #2 | Result #3 | Result #4 | Result #5 | Weight Factor for each characteristic (Average Value of distributed points) |
|---|---|---|---|---|---|---|
| On shore/ Off shore | 35 | 25 | 30 | 30 | 30 | 30 |
| Project Country | 20 | 25 | 20 | 20 | 15 | 20 |
| Plant Type | 20 | 20 | 25 | 15 | 20 | 20 |
| Project Duration | 15 | 10 | 10 | 5 | 10 | 10 |
| Scale Total | 5 | 10 | 10 | 15 | 10 | 10 |
| Equipment Quantity | 5 | 10 | 5 | 15 | 15 | 10 |

When the user enters a project information variable, the similarity score is calculated by the designed similar project selection criteria. The three projects with the highest scores are selected and provided with basic information such as plant type, duration and scale, and details such as plumbing drawings and man-hour information.

## 5 CONCLUSION

In this study, a man-hour prediction algorithm and tool for plant piping design was developed. The development process is as follows.

Step 1. Data collection: About 40 historical plant project data were collected.

Step 2. Develop a standard pipe design model and build a database: A database was built by standardizing the collected plant project data in a consistent format. The user can estimate the typical design man-hour by simply entering the required quantity.

Step 3. Development of correction factors: Country, Duration, and Scale Factors were developed using a machine learning algorithm.

By applying the coefficient to the general design man-hour value calculated in Step 2, we can obtain the design man-hour value that reflects the difference according to the project characteristics.

Step 4. Similar project recommendation function: select similar projects with the user's project based on project characteristic information and present as a reference.

This study is meaningful as it collects historical data and applies statistical analysis and machine learning algorithms in quantitative terms. Using the developed algorithm, project performers, such as EPC Company or Engineering Company, can relatively easily calculate design man-hours using limited information at the beginning of the bid.

## 6 LIMITATION AND FUTURE WORKS

As mentioned above, the scope of this study is basically to predict only the design man-hours corresponding to the piping discipline, and the other disciplines are replaced by the method using the ratio of design time between the discipline of commercial data. However, the correlation between project factors (period, etc.) and design time may vary depending on the type of work. Therefore, data on other types of work will be collected in the future, and studies should be conducted to find out the correlation between project types and overall design man-hours as well as each type of work. If data can be collected on a project basis, design man-hour trends by plant type and a customer can also be investigated. Existing regression and correction factors can also be improved.

## 7 Funding Acknowledgement

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# QUALITATIVE AND TRACEABLE CALCULATIONS FOR BUILDING CODES

**Beidi Li[1], Johannes Dimyadi[2], Robert Amor[3], and Carl Schultz [4]**

**Abstract:** We present a methodology and prototype software framework to formalise normative provisions related to building design and construction to support automated compliance audit processes of ISO-standard building information models (BIM). Our framework is based on the declarative Answer Set Programming (ASP) logic programming language that we extend to support optimised geometric and spatial reasoning. We address three key challenges in formalising building codes:

(1) Ambiguity and qualitative aspects of modern performance-based building codes, e.g. "Essential information on wayfinding must be easy to see, read and understand (BR15)"; "There shall be no direct line of sight between an access route and a WC (NZBC-G1)". Our framework supports integrated layers of abstraction (in the context of ontologies and knowledge engineering) in order to ground how behavioural and human-centred terms such as "easy to see" and "access route" are ultimately defined based on results from cognitive psychology and declarative spatial reasoning.

(2) Managing a relatively large code base that can support maintainability, extensibility, traceability, and transparency, i.e. a particular code definition can be easily traced back to research literature used for its formalisation, and indeed multiple alternative definitions can be implemented and checked simultaneously.

(3) Keeping the computational runtime efficient for practical applications, despite processing a large number of codes and a large size of real-world building models.

We present empirical results (including real building models from New Zealand) to demonstrate that formalised codes definitions can focus exclusively on the semantics without mixing in "tricks" to make them computationally faster for handling a large-scale BIM, which is often at the cost of clarity and code base maintainability, etc. Thus, we leverage the declarative character of ASP to achieve a total separation of (a) semantic definition from (b) computational runtime efficiency of conformance checking.

**Keywords:** Building Information Modelling, Automatic Code Checking.

## 1 PERFORMANCE-BASED BUILDING CODES

Performance-based building codes aim to reduce unnecessary costs of conservatism in complying with a limited range of prescriptive design solutions but are challenging from both interpretation and implementation perspectives (Meacham et al. 2005). In addition to being conveyed in natural language intended for human interpretation, provisions in performance-based codes are often qualitative and descriptive in nature. In order to

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translate a natural language statement into computer-readable codes, domain experts need to formalise them into logical propositions, deduce implicit properties from a building model, and apply formalised constraints to derived model parameters (Eastman et al. 2009). The manual process is not only time-consuming and fallible, but also hinders knowledge sharing and transfer in multi-platform, cross-disciplinary cooperation and collaboration in the Architecture, Engineering, Construction (AEC) industry (Dimyadi and Amor 2013).

Our primary contribution in this research is a building code formalisation approach that facilitates automated compliance checking, as follows:

- To separate the (formal) representation of a building code from its numerous disambiguating interpretations and enables every disambiguating interpretation to be traceable back to research literature. We achieve this by augmenting Building Information Modelling (BIM) models with *spatial artefacts* (Bhatt et al. 2012a; Bhatt et al. 2010);
- To separate the semantics of a formalised building code from computational (spatial) optimisations necessary for checking the code set against a large-scale BIM in practice. We achieve this by extending the code checking engine with in-built spatial processing optimisation features that are applied automatically "under the hood".

## 2 CHALLENGES IN AUTOMATIC CODE CHECKING APPLICATIONS

Consider the workflow illustrated in Figure 1 which reflects a common approach for formalising building codes (Yang and Xu 2004). This workflow firstly requires a systematic approach for mapping qualitative terms in a building code to instantiated building properties, and a systematic approach for executing the formalised rule and reporting the checking results.

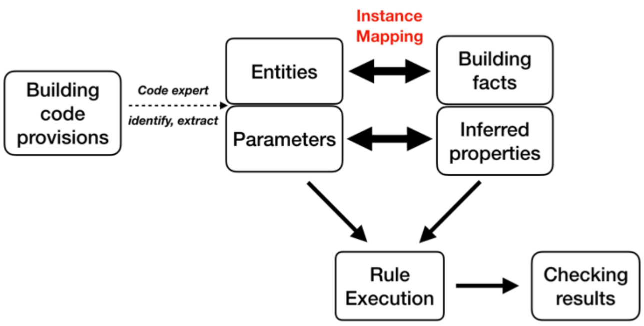


Figure 1. A common workflow for automated compliance checking of building codes.

We argue that the following two properties are essential for the body of formalised codes to be usable in practice, on a large community-wide scale, over a long period of time. We will use the following provision from the New Zealand Building Code (NZBC) as an illustrative example:

"*There shall be no direct line of sight between an access route or accessible route and a WC, urinal, bath, shower or bidet*".

**Desired property 1**: Whenever any (natural language) term is disambiguated, the rationale should be justified, and the justification should be readily traceable (e.g. to research literature in psychology, ergonomics, etc.).

Terms such as "direct line of sight" are qualitative and require disambiguation. Consider, for example, the range of eye heights of various occupants such as wheelchair users, walking children, walking adults, etc. Moreover, consider the possibility of visual reflections, the relevance of peripheral vision, whether a person using a bathroom facility should also be occluded, the visual system of a stationary versus a moving person, the precise definition of an access route, etc.

A comprehensive approach would be to provide numerous alternative (disambiguated) definitions of what "direct line of sight" means, with respect to a range of user groups, and maintain meta-data on the provenance of each definition. Compliance and non-compliance are then justified and traceable back to research literature. In contrast, ad hoc definitions, algorithms, and "magic numbers" used in disambiguation that are not clearly justified result in obscured deontic constraints and arbitrary evaluation criteria.

Our approach for systematic disambiguation, rather than to capture it at the code formalisation stage, is to extend instances of BIM with spatial artefacts, i.e. regions of empty space that carry information about human behaviour and experiences (Bhatt et al. 2012a; Bhatt et al. 2010; Bhatt et al. 2012b; Schultz and Bhatt 2013; Bhatt et al. 2014).

<u>Example</u>: Consider the region of empty space around an object such as a washbasin - this region is meaningful because a person must be located in that region to perform a particular act (e.g. washing hands). The geometry of this *functional space* region depends on properties of the person (consider wheelchair users, children, etc.), the task, and the object. Doors have an *operational space* required for opening and closing; people and sensors have *range spaces* (which can be further refined: visibility space, hearing space, etc.), and so on. These are examples of *spatial artefacts* (Bhatt et al. 2012a): regions of empty space that are rich with perceptual-locomotive semantics.

In our approach, the geometry of spatial artefacts is directly based on research literature in psychology and ergonomics (Kondyli et al. 2017; Kondyli et al 2018). This also enables the formalised code itself to remain closely aligned with the original natural language code.

**Desired property 2**: The formalised rule should, as closely as possible, reflect the source provision in the building code with no additional relational clauses added to facilitate the computational task of checking the code.

The computational task of checking a code provision against a BIM should not influence how the provision is represented formally in the code set. For example, suppose a first-order formalisation of the above NZBC provision is as follows, stating that it is a violation if bathroom object B is visible from corridor C:

```
Exists B,C in Objects :
  bathroom_object(B) and corridor(C) and visible_from(B,C) →
  violation(code(nzbc, privacy))
```

Now suppose this provision is checked against a large multi-storey BIM consisting of **n** corridor sections and **m** bathroom facilities. A naive code checking engine implementation will result in **n·m** visibility checks which is prohibitively expensive to run on large, real-world BIMs.

One solution is to include additional information in the formalisation itself, e.g. that the corridor and bathroom object should be on the same floor, and in the same rectangular visibility quadrant from a top-down floor plan perspective, i.e. a quad-tree cell division of building objects, where cells are merged if they are mutually visible:

```
Exists C,B in Objects :
 corridor(C) and bathroom_object(B) and
 same_floor(B,C) and same_2d_vis_quad_cell(B,C) and
 visible_from(B,C) →
 violation(code(nzbc, privacy))
```

While this provision can now be checked much faster, it has two serious drawbacks:

- The intended purpose of the provision (its semantics) is obscured by the added clauses making it significantly less comprehensible and extensible;
- The code set itself now depends on certain spatial data structures, and thus is significantly less portable, transparent, and maintainable.

The solution we advocate is to keep the initial, simple formalised code as is, and instead enhance the code checking engine with spatial data structure optimisations that are applied automatically.

## 2.1 Proposed framework and workflow

In contrast with state-of-the-art code checking practices, our framework proposes to map semantic code definitions to augmented building objects at the domain level, i.e. from regulatory ontology domain (*access route*, *line of sight*) to building ontology domain (*movement space*, *visibility space*). The separation of code semantics from enhanced model generation ensures that the code interpretation is accessible to regulation experts, and the code compliance assessment is verifiable by building experts independently. Figure 2 presents our workflow of translating textual requirements into formal rules that can be checked with respect to building instances.

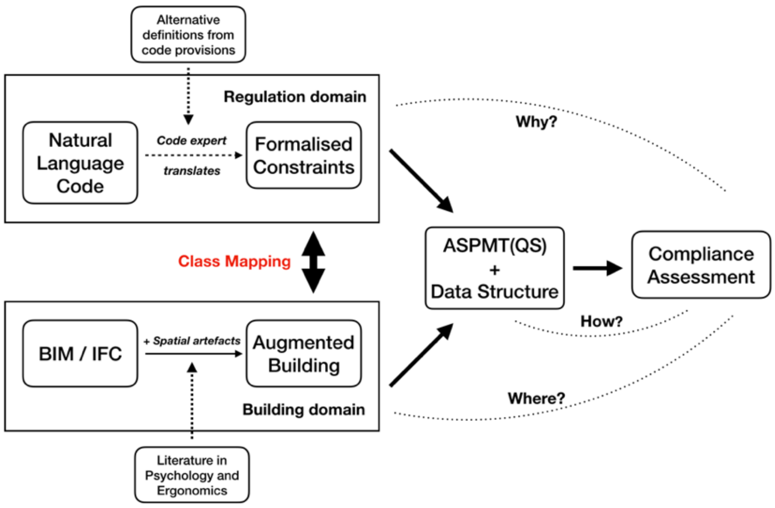


Figure 2. Proposed code checking workflow.

Firstly, code engineers enrich code provisions with meta-data, to capture the underlying semantics. This provides a unified, coherent way of interpreting qualitative terms, based on the chosen quantification of human experiences (vision, access) from legislative documents or literature research.

Secondly, the provision is translated into a predicate rule in the following form stating that all objects X satisfying preconditions P must demonstrate properties Q:

$$\textit{For all } X \textit{ in Objects: } P(X) \rightarrow Q(X)$$

Thirdly, object geometries, properties, and relationships are extracted from the building instance and declared as facts in the knowledge base. We then apply evidence-based deductive rules from literature (cognitive psychology, ergonomics) to enhance the building's representation with numerous modalities of actions permitted in the environment (hearing, viewing, manipulating, moving), captured through spatial artefacts.

Finally, we check the formalised rule against enhanced building objects using logic satisfiability solver extended with space, ASPMT(QS), and assess regulatory compliance (satisfiable, unsatisfiable).

Independent formulations of model facts, regulatory constraints, and deductive rules provide traceable rationales ("why"), transparent numerical computations ("how"), and rapid identification of code violations ("where").

In this paper we utilise the logic programming language Answer Set Programming extended to natively support spatial reasoning, ASPMT(QS) (Wałega et al. 2017; Wałega et al. 2015; Schultz et al. 2018), to implement our code compliance checking engine via automated non-monotonic reasoning. The declarative character of ASP allows the code formalisation to be open to alternative interpretations and user-defined rules, so that the checking system is portable and customisable.

In order to reduce runtime, we have further developed the core functionality of ASPMT(QS) with a general theory and framework of integrated spatial data structures for pre-processing building models and subsequently compute volumetric and topological relations of comparable objects. Examples of pre-processed spatial data structures include quad trees, R-trees, total orderings, containment hierarchies, etc. Spatial data structures are exploited in the form of additional constraints and optimisation techniques that are employed automatically by ASPMT(QS) as an integral part of its numerical and geometric computations used to determine spatial relationships. This enables building code experts to focus exclusively on the semantics of rules during code formalisation, and to ignore any computational runtime issues.

Our framework captures the general, abstract concept of spatial data structures (i.e. we do not commit to any particular data structure at this general level), and the general way in which they are exploited for more efficient geometric processing. Through this general framework we then define "instances" of spatial data structures that are actually employed during runtime – that is, our framework provides an extensible, flexible mechanism for incorporating a range of new spatial data structures in a uniform, mathematically rigorous manner.

## 3 EXTENDING BIM WITH SPATIAL ARTEFACTS

While BIM provides an annotated, relational structure representing a building's physical manifestation, building ontologies deal with physical, perceptual, and cognitive affordances of objects, e.g. a door is a place-transitioning object, a glazed panel permits mutual visibility, a wall is a place-delimiting object, etc. Such information is reflected in empty spaces, regions demarcated by theoretical limits of a user being able to interact with a given object. Driven by the NZBC code, we demonstrate the creation of three types of artefacts: movement space, visibility space, and functional space.

**Movement spaces** are series of rooms, corridors, and stairways connected by place-transitioning objects (doors, openings), conditioned by user-specific body schema, e.g. a door with a clear opening less than 760mm is considered non-transitable to a wheelchair user (DBH 2015). Movement spaces further depend on intrinsic properties of building components (slab inclination, floor-intersecting obstacles) that can be derived systematically and unequivocally from IFC-compliant components (Figure 3).

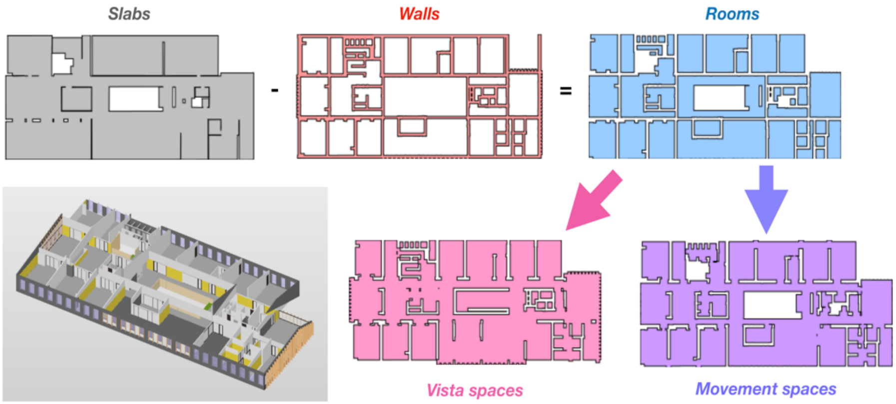


Figure 3. Construction of movement spaces from standardized physical representation of a real building.

The **visibility space** of an object is a closed, simple polyhedral region from which the object is viewable, depending on the observer's visual abilities (similar to the notion of isovists and viewsheds). We compute the unobstructed lines-of-sight from the object's boundaries as if seen by a person with perfect visual acuity and clip the region by an actual observer's visual range (Figure 4.a). Alternatively, Gibson's ecological theory suggests that visual perception depends on locomotion, i.e. the direction the observer is facing and the speed at which the observer is moving (Gibson 1954). This latter definition can be used to construct visibility spaces from an egocentric perspective, emphasising the effects of peripheral vision and vertical visual field.

The **functional space** of an object refers to the minimum clearances required for a human's physical activities in relation to the object (using a washbasin, grabbing handrails, opening a drawer, etc.). We infer the shape and position of functional spaces based on the object's geometry, the occupant's anthropometric properties, universal design guidelines, and ergonomics studies (Neufert and Neufert 2002). Such artefacts are represented as transparent blobs surrounding bathroom objects in Figure 4.e.

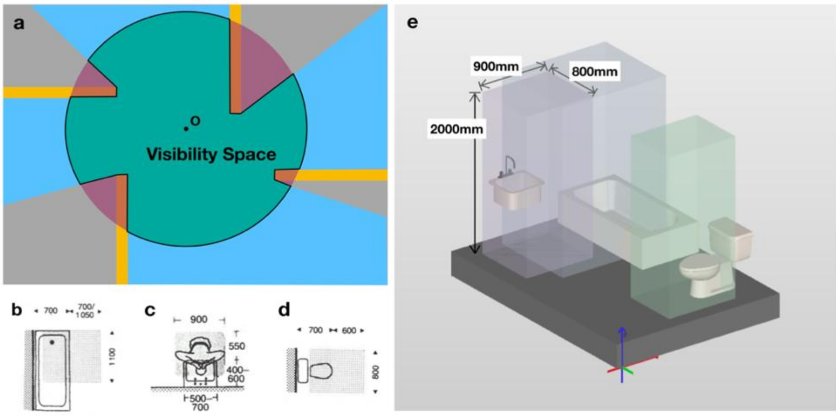


Figure 4. a) Visibility space of object O intercepted by the observer's visual range (green region); b-e) Spatial requirements for bathtub, basin, and toilet, figures taken directly from (Neufert and Neufert 2000); e) Visualization of functional spaces of bathroom objects.

Eliciting these spatial artefacts, the NZBC code is now translated into:

"*The visibility space of the functional space of a WC, urinal, bath, shower or bidet must be (topologically) disconnected from the movement space.*"

Such formalisation focuses exclusively on the semantics of the code provision, and systematically maps qualitative terms to classes of augmented building objects (*IfcSpatialArtefact*, a subtype of *IfcSpace*). Instances of *IfcSpatialArtefact* are then uniformly derived from a building's geometry based on empirical and experiential findings from the literature. In this way, we ensure a clear separation of rule interpretation, rule implementation, and rule execution.

## 4 EXTENDING LOGIC PROGRAMMING WITH NATIVE SPATIAL OPTIMISATION SUPPORT

In prominent collision detection algorithms such as Q-tree and R-tree (Winter 1999), the algorithm recursively restricts the conditions for interferences so that at each step, the algorithm retains false positives (potential clashes) and discards all true negatives (no clashes).

Using the same principles, we present a general spatial data structure framework that automatically generates necessary and sufficient conditions to a given "target" relation R, respectively denoted as $R_{NEC}$ and $R_{SUFF}$, that are less costly to evaluate than the exact definition $R_{DEF}$. In terms of material implication:

(1) $R_{SUFF} \rightarrow R_{DEF}$ (a sufficient relation implies the target relation)

(2) $R_{DEF} \rightarrow R_{NEC}$ (a necessary relation is implied by the target relation)

(3) $\neg R_{NEC} \rightarrow \neg R_{DEF}$ (contrapositive of necessity)

Therefore, $R_{SUFF}$ gives a shortcut to determine that $R_{DEF}$ holds, and the negation of $R_{NEC}$ gives a shortcut to determine that $R_{DEF}$ does not hold. From a set theoretic perspective, $R_{SUFF}$ represents all true positives, the complement of $R_{NEC}$ represents all true negatives, and the difference between $R_{NEC}$ and $R_{SUFF}$ represents undecidable cases that require a series of more refined sufficient and necessary conditions, the difference of which eventually, finally requires numerical evaluation with $R_{DEF}$ (Figure 5).

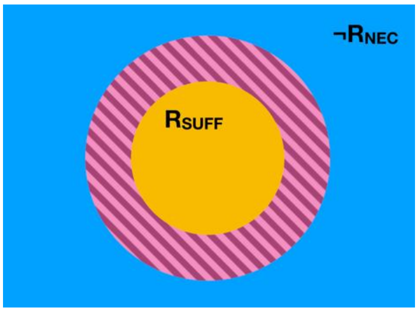


Figure 5. Boolean representation of relations $R_{NEC}$ and $R_{SUFF}$.

**Answer Set Programming**: ASP is a logic-programming paradigm developed within the artificial intelligence community that has its foundations in first-order logic (Brewka 2011). We use ASP by encoding a building as ASP facts, encoding building code compliance rules as ASP rules and constraints, and code compliance checking is implemented via ASP answer set search[5]. Our general formulation for spatial data structures is expressed in ASP as the follow logic programming rules and constraints:

```
R :- R_suff.

-R :- not R_nec.

R :- R_def.

:- R, -R.
```

## 4.1 Empirical test with circles

Now we test the operational aspects of our proposed spatial data structure framework with n randomly generated circles in a delimited rectangular region of the 2D plane. The goal is to enumerate all pairs of circles that overlap with each other as fast as possible.

The following is a simple demonstrative example of a *particular* spatial data structure that is used by following the *general* structure defined in our framework. We partition the region into k equisized clusters that are jointly exhaustive and pairwise disjoint, so that each circle is assigned to exactly one cluster containing its centre. If two circles are contained in non-adjacent clusters, they are necessarily disconnected. If two circles are concentric, they necessarily overlap.

In fact, checking cluster IDs (i.e. comparisons of numbers) is computationally much less costly than directly evaluating the exact definition of circle-circle intersection (i.e. a polynomial inequality of degree 2), this provides a shortcut to symbolically identify circle pairs that display trivially topological relations. Having run a series of tests, we

[5] Similar to Prolog, ASP has a knowledge base of facts and rules of the form: "Head :- Body." meaning that if the *Body* is true, then the *Head* must also be true. Rules with no *Head* are ASP constraints, written: ":- Body." meaning that the *Body* must not be true (i.e. as a logical expression: *Body* implies False). *Head* and *Body* expressions consist of literals, representing propositions that can be either True or False, and ASP reasoning engines are specifically designed to rapidly find combinations of deduced facts that are consistent with all given domain rules (referred to as models or answer sets). We have extended the base language of ASP beyond propositions so that a set of consistent facts must also be spatially consistent, e.g. a 2D point P can never be both inside, and outside, of a given circle C (Wałega et al. 2017; Walega et al. 2015; Schultz et al. 2018). In this paper we have further extended core functionality to automatically incorporate spatial data structures for efficient spatial reasoning.

empirically determine that the computational complexity decreases from $C_1 \cdot n^2$ to $C_2 \cdot n^2/k$, where $C_1$ and $C_2$ are some arbitrary constant factors. The ASP implementation is as follows:

**Sufficient condition**: The following rule states that concentric circles overlap:

```
overlap(C1, C2) :-
  circle(C1), circle(C2),
  centre(C1, (X1, Y1)), centre(C2, (X2, Y2)),
  X1 = X2, Y1 = Y2.
```

**Negated necessity**: The following rule states that circles in different clusters do not overlap:

```
-overlap(C1, C2) :-
  circle(C1), circle(C2),
  cluster(C1, K1), cluster(C2, K2),
  not adjacent(K1, K2).
```

**Relation definition**: The following rule implements the exact inequality that decides the overlap relation between two circles:

```
overlap(C1, C2) :-
  circle(C1), circle(C2),
  centre(C1, (X1, Y1)), centre(C2, (X2, Y2)),
  radius(C1, R1), radius(C2, R2),
  (X1-X2)*(X1-X2)+(Y1-Y2)*(Y1-Y2) < (R1+R2)*(R1+R2).
```

We implement the simple cluster partitioning strategy in ASP (Figure 6). Our empirical experiments show that average runtimes rapidly decrease with large number of clusters[6] (Figure 7). For $10^4$ circles, clingo runtime drops from 17.1 seconds with no clusters (K = 1) to 4.2 seconds with 10 clusters (K = 10); for $2 \cdot 10^4$ circles, runtime drops from 60.5 seconds with no clusters to 18.7 seconds with 10 clusters; for $5 \cdot 10^4$ circles, runtime drops from 457.6 seconds with no clusters to 133.6 seconds with 10 clusters, resulting in an average decrease by factor 3.

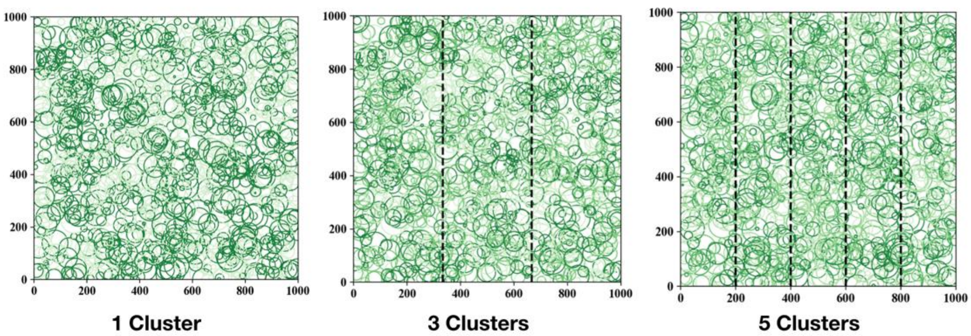


Figure 6. Horizontal clustering of circles with K = 1, 3, 5.

[6] We ran our empirical experiments on a Mac Book Pro with Mac OS 10.13.6, processor 2.2 GHz Intel Core i7, and 16GB RAM.

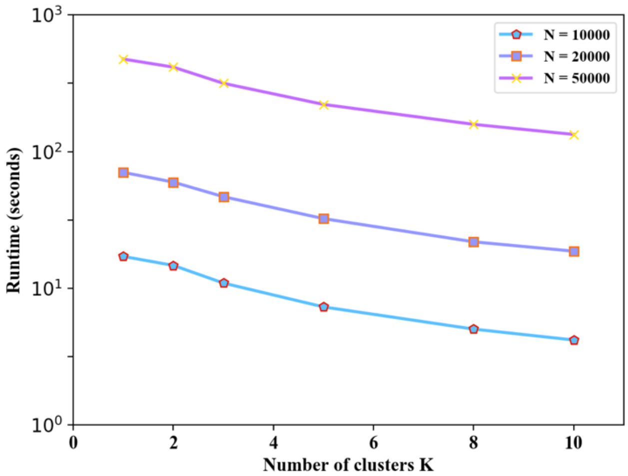


Figure 7. Runtimes of the all overlapping circles test for K = 1, 2, 3, 5, 8, 10 and N = 10000, 20000, 50000 with *clingo*.

## 4.2 Scalability test with a real building model

Now let's take another look at the formalised NZBC rule asserting that there should be no direct line of sight between an access route or accessible route[7] and the vicinity of a bathroom object that a user may occupy during its usage. Moreover, acceptable solutions allude to the procedural complexity in checking such requirement, e.g. a single use sanitary facility can be visually separated solely by an opaque door, whereas a space containing multiple cubicles should include additional screens for visual privacy.

As seen Section 2 and 3, ambiguous terms (line of sight, access, vicinity) in the new code formulation require diligent consideration of every combination of user, activity, and situation. As the code introduces accessible route that is applicable to people with disabilities, we are further to incorporate physiological evidence of one's body measurement (height, encumberment, etc.) into our semantic formalisation. Similarly, functional spaces and visibility spaces vary greatly depending on occupant's perceptual-locomotive abilities and are constrained by local spatial configurations (sloped roof, handrails, sanitary bins, etc.). We define the following predicates:

*Movement_Space(Occupant)*

One movement space predicate is defined for each Occupant value: "Children", "Adults", "People with dementia", "Elderly people", "Patients with crutches".

*Functional_Space(Sanitary_Fixture)*

One functional space predicate is defined for each instance of sanitary fixtures taking the following type values: "WC with external cistern", "Enclosed shower", "Open shower", "Bidet", "Urinal", "Wall-hung basin".

*Visibility_Space(Object, Observer)*

One visibility space predicate is defined for each instance of Object and Observer, where Observer can take the values: "Fully-sighted", "Children", "People with peripheral vision loss".

In relation to particular building instances, we employ psychology findings to semantically enrich the building representation with spatial artefacts.

[7] People whose ability to use buildings is affected by mental, physical, hearing or sight impairment.

In practice, we first identify bathroom objects labelled as *IfcFlowTerminal* and infer the shape of regions in which a user can engage in material contact with the object, characterised by action's modality, e.g. approach, attainment, operation, manipulation (Ginnerup 2009), denoted as *IfcFunctionalSpace*. We then compute the regions visible from the outer boundaries of I*fcFunctionalSpace*, depending on individual occupant's visual acuity, eye level, and head movement, denoted as *IfcVisibilitySpace*. After that, we extract access routes from the building's walkable surfaces, floor-intersecting obstacles, and place-transitioning objects, denoted as *IfcMovementSpace*. Finally, we test intersections between *IfcVisibilitySpace* and *IfcMovementSpace*.

A proof-of-concept implementation with a two-storey building in the city of Christchurch, New Zealand has identified 2 stairs, 1 atrium, and 2 corridors, 87 sanitary fixtures, of which 12 showers, 17 bathrooms, and 17 basins. We derive 245 functional spaces of bathroom objects, 490 visibility spaces of such functional spaces, and 100 movement spaces, based on the building geometry and user-specific data.

A naive approach for checking compliance attempts to compute the exact intersections between all pairs of comparable polyhedral meshes, which is laborious and subject to numerical instability issues.

Based on our previous empirical test results, we propose a series of increasingly constricting necessary and sufficient conditions that efficiently prune the search space. Concretely:

- Two meshes are necessarily disconnected if their axis-aligned bounding boxes (AABB) are disconnected;
- Two meshes are disconnected if their 2D projections are disconnected;
- Two polygons A and B are disconnected if A is a proper part of one of B's holes;
- Two polygons A and B overlap (not disconnected) if A contains one of B's holes, etc.

In the absence of obvious shortcuts, one may still apply advanced collision detection algorithms such as overlapping AABB (Luo et al. 2011) to shrink the region where interferences may occur. Exact calculations will be used as a last resort to decide if two meshes overlap. The ASP implementation is as follows:

Relation R1 is implemented as:

```
comparable(V, M) :-
  bathroom_object(O), functional_space(O, F),
  visibility_space(F, V), movement_space(M).
```

Relations R2 are implemented as:

```
overlap_(C1, C2) :-
  axis_aligned_bounding_box(C1, (Xmin1,Xmax1,Ymin1,Ymax1,Zmin1,Zmax1)),
  axis_aligned_bounding_box(C2, (Xmin2,Xmax2,Ymin2,Ymax2,Zmin2,Zmax2)),
  Xmax2 > Xmin1, Xmin2 < Xmax1,
  Ymax2 > Ymin1, Ymin2 < Ymax1,
  Zmax2 > Zmin1, Zmin2 < Zmax1.
```

```
part_of(C1, C2) :-
  axis_aligned_bounding_box(C1, (Xmin1,Xmax1,Ymin1,Ymax1,Zmin1,Zmax1)),
  axis_aligned_bounding_box(C2, (Xmin2,Xmax2,Ymin2,Ymax2,Zmin2,Zmax2)),
  Xmin1 >= Xmin2, Xmax1 <= Xmax2,
  Ymin1 >= Ymin2, Ymax1 <= Ymax2,
  Zmin1 >= Zmin2, Zmax1 <= Ymax2.

disconnected(A, B) :-
  comparable(A, B), not overlap_(BA, BB).

disconnected(A, B) :-
  comparable(A, B), hole(B, HB), part_of(A, HB).

-disconnected(A, B) :-
  comparable(A, B), hole(B, HB), part_of(HB, A).
...
disconnected(A, B) :-
  comparable(A, B), intersect(MA, MB, I),I = spatial_void.
```

Relation R3 is implemented as:

```
violation(NZBC, privacy) :- comparable(V, M), not disconnected(V, M).
```

We now have a clear formulation of code semantics R1 that can take alternative definitions, a set of rules R2 that automatically integrates optimisation in numerical evaluation of fully grounded variables, and a rule R3 that indicates facts in the actual building contradict regulatory requirements.

Table 1 shows runtime before and after introducing the data structure. The objects have been extracted from the IFC model and manually edited to resolve geometric discrepancies. For the sake of simplicity, we only show results from intersection checks between 2D projections of visibility spaces and movement spaces in a single storey. Figure 8 shows representative cases where visibility spaces and movement spaces match with necessary or sufficient conditions of “disconnected” so that exact computations of intersection can be avoided.

Table 1. Model specifications and runtimes in clingo of evaluating the building code visibility requirement on the two-story building in Christchurch.

| | |
|---|---|
| Average number of vertices in visibility spaces | 61 |
| Average number of vertices in movement spaces | 127 |
| Average runtime without spatial data structures | 9.297 seconds |
| Average runtime with spatial data structures | **1.579** seconds |

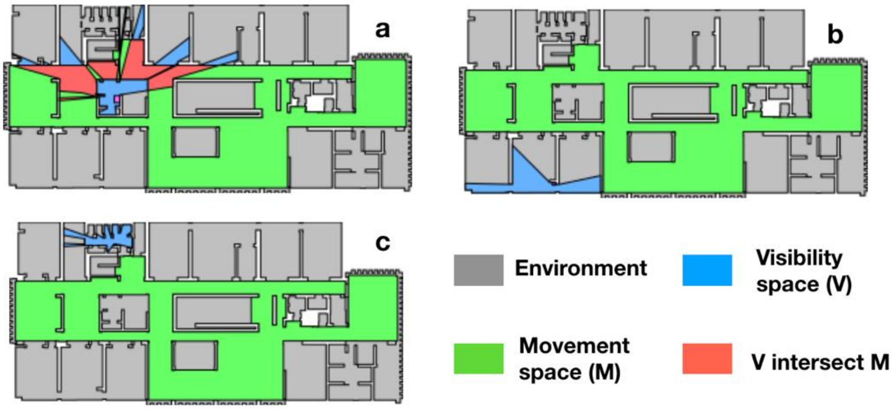


Figure 8. Necessary contact between visibility space V and movement space M: a) V overlaps with a hole in M. Necessary disconnectedness between V and M: b) M contains no vertices in the overlapping AABB of V and M; c) V and M have disconnected axis-aligned bounding boxes.

## 5 RELATED WORK AND CONCLUSIONS

Regulatory compliance, as a major concern to professionals in the AEC industry, provides statutory, contractual performance objectives that building design must provide for a variety of occupant types and use cases (Beach et al. 2015). The task of automatic code checking requires encoding textual regulations as a constraint that is systematically checkable and verifiable with respect to digital information acquired about a building.

However, the maintenance of a voluminous code base with respect to real world buildings is facing serious drawbacks in terms of insufficient deployment of industry standards and lack of adequate implementation support (Preidel and Borrmann 2016). Challenges in automatic and semi-automatic code checking include but are not limited to: conflicting shape representation, inconsistent object classification, rule abstraction and required tool complexity, obscure semantic mapping, continuous updates in legislative documents, etc. (Sacks et al. 2017; Dimyadi et al. 2016; Solihin and Eastman 2015). In addition, state-of-the-art automatic code checking software systems often embrace an ad hoc approach of deriving model views required to run an encoded query (Eastman 2009), which makes the checking results subject to obscured rule interpretation and untraceable numerical assumptions. Furthermore, most theoretical frameworks have been developed in a specific context targeting one single aspect of regulatory conformance (structural soundness, safety, thermal performance), this further prohibits rule sets to be reused and shared among different communities (Solihin and Eastman 2015; Zhang et al. 2013; Pauwels et al. 2011). Therefore, it has become evident that a modular, extensible, and transparent system is needed for rule interpretation, and a reliable, coherent, operational logic-based system for rule checking.

In this paper, we proposed to leverage the strength of a (pure) semantic code formalisation to maintain a clean, modifiable code base. To achieve this, we extended ASPMT(QS) with a framework for spatial data structures to embed optimisations directly within the reasoning engine. We demonstrated the operational aspects of our framework with an industry-scale building and a qualitative, descriptive constraint on bathroom user's privacy from the NZBC. The ASP rule that was checked was a "pure" encoding of the original building code rule, containing no additional clauses concerning computational runtime and thus more closely aligns with the natural language code description. Our empirical results show a 4-factor speed up when the spatial data structure optimisations were built into the ASP search engine.

This paper belongs to a series of research efforts specifically aiming to provide a standard-compliant code checking system that allows a regulation expert to define a rule, execute the rule, and explain how the rule is applied and why the rule has passed, failed, or inconclusive based on available information. As we quickly touched upon in 4.2, rule semantics are a complex subject that display layers of abstraction including procedural complexity, defeasible principles, tolerances, etc. (Sacks et al. 2017; Dimyadi et al. 2017), and we intend to meticulously address these issues in coming studies.

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# CLASSIFYING IFC ENTITIES BY THEIR RELATIVE IMPORTANCE FOR ACCURATE INTEROPERABILITY MEASUREMENT

**Joseph Jabin[1], Johannes Dimyadi[2] and Robert Amor[3]**

**Abstract:** The IFC data model has several hundred entities and thousands of attributes, relationships, quantity and property sets that can represent various aspects of a construction project. A one-to-one mapping between a BIM software tool's native data format and the IFC data exchange standard is not possible. This complexity makes it difficult for the translator modules in a BIM software tool to accurately map the IFC elements, causing interoperability problems while exchanging BIM data using IFC. Also, there are mistakes made by the software developers in implementing the mapping to and from IFC data exchange standard, which adds to the issue. A proposed approach to tackle the interoperability problem is to adopt a 'divide and conquer' method by classifying IFC entities as per their relative importance for a discipline and to rectify the interoperability issues of the most important entities first. This paper proposes a framework to classify the IFC entities as per their relative importance with respect to various disciplines and introduce an index called `RI` (Relative Importance). This paper also suggests the application of the proposed framework in the interoperability measurement (conformance testing) implementation for BIM software tools, and in presenting the results of conformance tests.

**Keywords:** BIM, Relative importance, Interoperability measurement, Framework, IFC classification.

## 1 Introduction

There are numerous Building Information Modelling (BIM) software tools currently available. Data exchange between those BIM software tools is crucial for collaboration between various disciplines in Architectural, Engineering, Construction, and Facility Management (AEC-FM) industries. Industry Foundation Classes (IFC) were introduced for this purpose and have become the de-facto standard for data exchange between various BIM software tools (Lai and Deng, 2018). The IFC data model has several hundred entities and thousands of attributes, relationships, quantity and property sets that can represent various aspects of a construction project. Data accuracy during a data exchange is of the utmost importance when commercial projects rely on IFC as a mechanism to reliably exchange their BIM models between various BIM software tools (Amor, Jiang, and Chen, 2007). However, the translation modules of BIM software tools do not always accurately map the elements of a BIM model onto the IFC data structure during data exchange. In general, this is because a complete mapping is not possible, but

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also due to mistakes made in implementing the mapping to and from IFC data exchange standard. There is a significantly large number of possible mappings between various entities and their attributes that makes it extremely hard to completely address the interoperability problem.

This research adopts a 'divide and conquer' problem solving approach to tackle the interoperability problem by classifying IFC entities according to their importance to a particular discipline and to identify the interoperability problems associated with entities in the higher level of importance first. The 'more important IFC entities' in this context are those that can have a more significant negative impact on the project if there were any unintended alteration during data exchange. The insight for this type of classification was gained from software testing principles where modules to be tested are classified based on their impact on the safety and reliability of the final software system.

This paper proposes a novel framework to classify IFC entities along with their attributes and property sets based on their importance to a particular discipline. Classifying the IFC entities and properties is a complex process that requires significant effort, and it will take a long time to classify the majority of the elements because the importance of an IFC entity changes with different disciplines and processes. The framework incorporates methods to overcome the complexities described above by introducing a relative importance index to quantify the relative importance of IFC elements. This paper also suggests two areas of application for the proposed framework: in the interoperability measurement (conformance testing) implementation for BIM software tools; and in presenting the results of conformance tests.

## 2 Background

Building Information Modelling (BIM) is a multi-faceted technology and process that enables the sharing of the physical and functional representation of a built environment throughout its life cycle. The objects of BIM processes are building models or BIM models (Sacks, Eastman, Lee, and Teicholz, 2018). There are numerous software tools currently available to create and manipulate these BIM models. A construction project needs a multitude of these BIM software tools to assist the execution of the project and will need BIM models to be exchanged between these software tools (Lipman, 2006). Interoperability between BIM software tools is a crucial requirement for AEC-FM industries to enhance their efficiency and to support new business processes (Amor, 2008). Data can be exchanged directly between these BIM tools by implementing one set of translators between each pair of software tools to map the native representation of the BIM model of one software tool to the native representation of the other. Developing and maintaining numerous sets of translators for direct data exchange between various software tools is extremely inefficient (Laakso and Kiviniemi, 2012). Hence, the preferred method of exchanging data between BIM software tools is to have a data exchange standard so that each software tool only needs to implement one translator specifically for that standard.

The Industry Foundation Classes (IFC) is one of the data exchange standards that was introduced to achieve interoperability in AEC-FM industries. IFC was developed and is maintained and controlled by an industry consortium known as buildingSMART (formerly IAI). The AEC-FM industries in many countries and the majority of the BIM software tool vendors have adopted IFC as their preferred data exchange standard, and strong government-level policies and mandates are in place in many countries to ensure the adoption of this standard (Amor et al., 2007). The first version of IFC (IFC1.0) was released in 1997, and it has been developed and updated periodically. The initial versions only supported basic architectural elements such as wall, floors, doors, windows, beams, and columns (Lipman, 2006). Further versions enhanced its capability to represent building components, fixtures, and equipment in various disciplines such as HVAC, Plumbing, Electrical, Mechanical, as well as Facilities management. The current candidate standard IFC4.2 has included entities to represent bridges (buildingSMART, 2019d). The increase in the capability of the IFC schema to represent more building elements and processes resulted in a significant increase in the number of the entities, attributes, property sets, and relations in the IFC schema (Amor, 2015). The current official release of IFC version has 801 entities, 413 property sets, 93 Quantity sets, and 1694 Individual properties (buildingSMART, 2019c).

The evolution of IFC into an increasingly complex schema has negatively impacted the ability of the BIM tool's translator systems to correctly handle IFC data, which is a crucial aspect of the maturity of the BIM marketplace and the confidence of the industry to work with IFC data models (Amor et al., 2007; Amor, 2015). Exchanging data between BIM software tools and the IFC data model is a highly complex process as the translators cannot have a one-to-one mapping between the software tool's native data format and the IFC schema; and also in many cases, there can be multiple possible mappings for the same elements between native and IFC schemas (Lai and Deng, 2018). Hence, it is challenging for software vendors to develop and maintain translators that can accurately handle the IFC data. Many studies since the mid-2000s have pointed out translation errors that have caused data loss and misinterpretation of intent (Amor and Ma, 2006; Lai and Deng, 2018).

The interoperability issues caused by the inaccurate translation by BIM tools have created a psychological barrier for the wholehearted adoption of BIM by the industry (Solihin, Eastman, and Lee, 2015). Hence, it is critical that the translation process be improved to gain the confidence of the AEC-FM industries. However, the software industry is well aware that it is impossible to create error-free software (Amor, 2015). It is also challenging to correct all the errors, because the removal of a fault in a software product may affect the existence, number, location and nature of other faults in that software (Mili and Tchier, 2015, p. 287). Also, the fact that translators of the various design tools are constantly changing (Amor et al., 2007), and the increase in the number of IFC elements with each version updates adds to the complexity of the situation (Amor, 2015). buildingSMART is aware of this issue and has introduced methods to reduce the scope of information exchanges and to make IFC data exchanges manageable (Laakso and Kiviniemi, 2011). The Model View Definition (MVD) mechanism was introduced to reduce the complexity of the IFC schema in applications by focusing only on a subset required by a specific discipline (e.g., structural analysis) or for a specific application (e.g., project and design coordination). Thus, MVD can be viewed as a type of 'divide and conquer' solution to improving interoperability. However, current approved MVD are practically still too complex to handle as a single unit for the purposes of troubleshooting translation errors in BIM software tools.

Insights to improve the accuracy of the IFC translators can be gained from the software testing discipline. Software testing suggests that not all errors carry the same stakes even for the same stakeholders, let alone for different stakeholders (Mili and Tchier, 2015, p. 300). Since different errors in software impact each stakeholder differently, the software testing discipline advises the software testers to target the high impact errors before correcting lower impact errors in software (Mili and Tchier, 2015, p. 288). Similarly, in BIM, "not all errors are equal in terms of their impact downstream to the receiving application within the exchange workflow" (Solihin et al., 2015). For example, during an IFC data exchange, a missing or altered structural element of a building such as a load-bearing beam will have a higher impact on the integrity and stability of the building than a missing or altered non-load-bearing beam for a stakeholder in the structural engineering discipline. However, any alteration during data exchange for the same non-load-bearing beam may have a higher impact on the execution cost (but less on safety aspects) for a non-structural stakeholder. Likewise, a missing piece of furniture in the data exchange may only have a negligible impact to the interior designer, and no impact at all to the other stakeholders. Thus, each IFC element has different levels of importance relative to the discipline they are associated with, in terms of the impact caused by an alteration of data during an IFC data exchange. Therefore, as suggested by the software testing discipline, the translation error of an IFC element that has higher importance for a particular discipline should be targeted before correcting translation errors of IFC elements with lesser relative importance. Currently, the only mechanism to group IFC elements as a subset of the IFC schema is an MVD. However, elements in an MVD do not vary in their level of importance, and there are no methods available to further segregate IFC elements as per their relative importance to each other. Hence, this research introduces a 'Relative Importance' framework to classify IFC elements as per their relative importance to each other with respect to their perceived impact on different disciplines.

## 3 THE RELATIVE IMPORTANCE (`RI`) FRAMEWORK

A relative importance (`RI`) framework is proposed to overcome the complexities described in the previous section and to help improve the accuracy of the translators in BIM software tools. Different parts of a system have different degrees of importance as per each component's significance or criticality in the system, and the difference in importance needs to be recognised by giving a weightage to each component (Pridmore and Rumens, 1989). Hence, this framework introduces an index called 'Relative Importance' (`RI`) to give due weighting to IFC elements to recognise the difference in the importance of each IFC component in the whole building system.

This index can be used for enhancing the interoperability measurement process in a conformance test. Interoperability measurement is the process of measuring the correctness of data exchange given a set of criteria. To accurately measure the correctness of the data exchange during a conformance test, the measurement process is to be conducted as per the principles established by measurement theories (Fenton and Pfleeger, 1997; Tal, 2017). Measuring interoperability between a BIM software tool and IFC data exchange standard as per measurement theory has three main steps (Fenton and Pfleeger, 1997; Jabin, Dimyadi, and Amor, 2019; Tal, 2017), (1) quantify how accurately the translator systems in the BIM software tool maps its native representation to the IFC data exchange standard. The outcome of this process is known as 'quantified indications' (Tal, 2017). (2) Convert quantified indications into a measurement outcome using a 'measurement model'. A measurement model is used to abstract away the complexities of the quantified indications (Fenton and Pfleeger, 1997) and present the outcome in a manner understandable by the end-user. (3) Represent the measure derived using the measurement model on a particular scale which is known as the 'measurement outcome' (Jabin et al., 2019; Tal, 2017). Since the relative importance index needs to be used in all of the measurement processes, the notation for the index is designed in two different ways to differentiate where the indexes are being used. The relative importance index used to represent the values in calculation steps (first and second steps of the measurement process) shall be represented using the notation 'ri'; and the measurement outcome represented on a particular scale (third step of the measurement) which has abstracted away all the complications and calculations of the measurement process shall be represented using the notation 'RI'.

As mentioned in the previous section, the relative importance of the same IFC element changes with each discipline from which the elements are viewed from. Therefore, the values of RI or ri are always dependent on the perspective of the discipline it is viewed from. Hence, the respective discipline needs to be represented along with the notation. Thus, RI and ri notations shall be written as $RI_d$ and $ri_d$ where the subscript 'd' is a placeholder to denote the name of the discipline for which the relative importance of IFC elements are derived from. For example, if the relative importance values are derived from the perspective of Structural engineering discipline, it will be denoted as $RI_{Structural}$ or $ri_{Structural}$. The next section explains how the $RI_d$ and $ri_d$ indexes can be used to enhance the interoperability measurement process.

## 4 IMPLEMENTATION OF THE RI FRAMEWORK

The first step to improve data exchange accuracy is to quantify errors in the translator. This is effectively measuring the interoperability between a BIM software tool and the IFC data exchange standard. Specific conformance tests designed to measure the interoperability for a particular data exchange standard are conducted by various researchers and organisations. Conformance testing is conducted by one of the following three methods: 1) checking for accurate translation of a test model exported from the native file format to an IFC file by a BIM software tool, or 2) checking the accuracy of translation of a test model imported into the native file format from an IFC file by a BIM software tool, or 3) importing an IFC file into the native file format of a BIM software tool and immediately exporting it back to IFC file format (round-trip) and comparing the original against the re-exported IFC file for changes. (Lipman, Palmer, and Palacios, 2010). The primary output of these tests will be a list of quantified indications which denotes the correctly and incorrectly translated IFC elements (the first step of measurement). These results are intended for the end-users to be aware of the translator issues, and more importantly, intended for the software developers to correct the errors found during the translation.

The official conformance test to certify BIM software tools on their capability for correct data exchange with the IFC data exchange format is conducted by buildingSMART (buildingSMART, 2019b). The test results are published online as a list of conforming and non-conforming IFC elements (or concepts as they are called in the report). Also, buildingSMART awards a certificate to the vendor of the compliant software, and the vendor can display a certified logo on their software products to indicate to customers that the software is conforming to the IFC data exchange standard (buildingSMART, 2019a). Eventhough a certified logo and certificate conveys the impression that certified BIM software tools can accurately exchange data with the IFC data exchange standard, numerous researchers have conducted independent conformance tests and discovered critical errors in the translation systems of many BIM software tools certified by buildingSMART (Amor and Dimyadi, 2010; Jeong, Eastman, Sacks, and Kaner, 2009; Kiviniemi, 2008; Lai and Deng, 2018; Lipman et al., 2010; Ma, Ha, Chung, and Amor, 2006). It is to be noted that the conformance test report that buildingSMART publishes does show that some of the IFC elements are not supported, or is only partially supported (or restricted as called in the report) by the BIM software tools being tested and certified. It means that the certified BIM software tool will cause some interopreablity issues when data is exchanged using the unsupported IFC elements. However, this infomation that the certified software tool was certified with some unsupported IFC elements is not explicitily conveyed in the certification logo or marketing materials provided by the vendors. Therefore, the end-users are not able to correctly interpret the conformance test results making them unable to accurately assess the data exchange accuracy of the BIM tools they use.

Hence, it is crucial that a conformance test output should be able to explicitly convey the data exchange accuracy and data exchange limitations of the certified BIM software tool. The $RI_d$ framework can be used to augment the conformance test reports to make it more meaningful for the end-users and software developers. The next section demonstrates an example approach to how the $RI_d$ framework can enhance the meaning of the interoperability measurement outcome. It also describes how the result of a conformance test could be displayed in a meaningful manner, along with the current certification logo (issued by buildingSMART).

## 4.1 $RI_d$ framework to enhance the meaning of interoperability measurement outcome

The first step to implement the $RI_d$ framework is to classify the IFC elements along with their attributes and property sets as per their relative importance by assigning $ri_d$ values for each of them. Since the $RI_d$ framework is being introduced to manage the complexities of the IFC data model, it is preferred to follow a minimalistic approach for the concepts involved within the framework. Therefore, the granularity for the $RI_d$ framework for differentiating the relative importance levels of IFC elements is kept to just three levels; which are 'Low', 'Med', and 'High', which can be equated numerically as 1, 2, and 3 respectively. The assigned $ri_d$ values will be influencing calculations done for the interoperability measurement and will determine how the conformance test results are shown to the end-users. Also, these values serve as an indicator for the software developers to help them understand the importance of IFC elements from the perspective of various disciplines.

The importance level of each IFC element and its attributes should be assigned by an expert in each discipline based on their acceptable tolerance for any inaccuracy during data exchange with IFC. When an IFC element is directly related to a discipline and needs to be exchanged precisely, the element is considered as high importance for that discipline and would be assigned a $ri_d$ value of 3 (high importance). Directly related elements are those elements which are directly used by the discipline. For example, elements such as pipes, pipe joints, etc. are directly related to plumbing discipline, and load-bearing beams, columns, walls, slabs, etc. are directly related to structural discipline. Also, there will be many elements that are indirectly related and important to a specific discipline. These indirectly related elements would be assigned a $ri_d$ value of 2. For example, the plumbing contractor needs the structural layout data of load-bearing beams to locate the position where structural penetrations could be made to allow the pipes to pass through the beams. These positions on a load-bearing beam are designed in such a way that the structural penetrations do not cut the reinforcement bars inside them. If there are any unintended alterations during data exchange to the marked positions, the plumbing contractor might make the penetration in the wrong position on the beam and may cut the reinforcement bars inside it, causing damage to the beam. Thus, the accuracy of structural data is also important to the plumbing discipline, though not as important as the data of the elements directly related to the discipline. Hence, a $ri_d$ value of 2 (medium importance) is assigned to structural elements when viewed from the perspective of the plumbing discipline. All other elements that are not related to the plumbing discipline would be assigned a $ri_d$ value of 1 (low importance). The assignment of $ri_d$ values will be a one-time process for each version of a schema (e.g., IFC 4.1) for each discipline. The $ri_d$ values decided by experts should be assigned at the IFC schema level, and preferably verified and maintained by the organisation that manages the IFC standard.

Table 1 shows a sample assignment of the $ri_d$ values for three IFC elements (E1, E2, and E3) along with their attributes. In a real implementation, 'E1.PropertySet1.property = xxx' listed in column 1 could be substituted with a real IFC property set and its value, e.g., 'IfcBeam.Pset_BeamCommon.LoadBearing = True'. The assignment of $ri_d$ value for this element value combination will be based on the importance of a loadbearing beam from the perspective of various disciplines.

Table 1. An example allocation of $ri_d$ values by disciplines.

| IFC Elements | $ri_{Structural}$ | $ri_{Interior}$ | $ri_{Plumbing}$ |
|---|---|---|---|
| E1.PropertySet1.property = xxx | 3 | 1 | 1 |
| E1.PropertySet2. property = xxx | 1 | 3 | 1 |
| E2. PropertySet1.property = xxx | 2 | 2 | 1 |
| E2. PropertySet2.property = xxx | 3 | 1 | 2 |
| E2. PropertySet3.property = xxx | 1 | 2 | 1 |
| E2.QuantitySet1.Quantity = xxx | 1 | 2 | 3 |
| E3.QuantitySet1.Quantity = xxx | 1 | 2 | 3 |

For example, any data associated with a load-bearing beam is of high importance to the structural discipline, and therefore should be translated exactly as it is. Hence, a $ri_d$ value of '3' would be assigned for the element 'IfcBeam.Pset_BeamCommon.LoadBearing = True' and the assignment will be listed under '$ri_{Structural}$'. Therefore, in Table 1, when $ri_d$ value of '3' is assigned for 'E1.PropertySet1.property = xxx' (Row 1) under $ri_{Structural}$, it implies that all IFC elements with that particular property and value occurring in an IFC file will be considered high importance for stakeholders in the Structural discipline. Hence, following the previous example, all the IfcBeam elements with the property LoadBearing=true will be considered as high importance for the Structural discipline. Similarly, if the accuracy of an element is not of concern for a particular discipline, then it can be assigned a $ri_d$ value of 1. For example, a load-bearing beam is not a concern for an interior works contractor; hence $ri_{Interior}$ shall be assigned a value of '1', and all other elements shall be assigned $ri_d$ values using the same principle.

The next step in the implementation of the $RI_d$ framework is to map the results of an interoperability measurement test conducted between a BIM software tool and IFC data exchange standard to the $ri_d$ values. Since this paper focuses on the theoretical implementation of the $RI_d$ framework, a comprehensive interoperability test has not yet been conducted; instead, sample test data was chosen taking insights from literature on actual interoperability measurements (Amor et al., 2007; Jeong et al., 2009; Lai and Deng, 2018; Ma et al., 2006). A common method adopted by researchers to represent the interoperability measurement output is to list out the number of correctly or incorrectly (or both) translated elements. All the tests in these research projects were done using one of the three conformance testing methods described in section 4. Table 2 lists out an exemplar outcome of an interoperability measurement test conducted using a round-trip test for demonstrating a sample implementation of the $RI_d$ framework. The first column of the table lists three types of IFC entities (E1, E2, and E3) along with their attributes and values that were present in the test models used for the round-trip test. The second column lists the number of total elements (N) tested of the corresponding element and attribute value in column 1 (e.g., the total number of IfcBeams with property Beam.Loadbearing=true), and the third column lists the total number of correctly translated elements (n) out of (N).

Table 2. Exemplar outcome of a round-trip test.

| IFC Elements | Total No. of elements tested | No. of correctly translated elements |
|---|---|---|
| | N | n |
| E1.PropertySet1.property = xxx | 1500 | 1450 |
| E1.PropertySet2. property = xxx | 225 | 200 |
| E2. PropertySet1.property = xxx | 5000 | 4250 |
| E2. PropertySet2.property = xxx | 500 | 499 |
| E2. PropertySet3.property = xxx | 3250 | 3200 |
| E2.QuantitySet1.Quantity = xxx | 75 | 60 |
| E3.QuantitySet1.Quantity = xxx | 125 | 100 |

To determine the $ri_d$ value of the elements listed in Table 2, a row by row calculation is performed against the corresponding $ri_d$ values listed in Table 1. Table 3 shows the mapped $ri_d$ values for the Structural discipline. Also, the sum of the total number of elements which has been assigned the same $ri_d$ value is calculated from the table ($\Sigma$N and $\Sigma$n). The same process is applied to all the disciplines for which a measurement outcome is needed.

Table 3. Calculations for $ri_d$ values for the Structural discipline.

| IFC Elements | $ri_{Structural}$ | N | n | $\Sigma N$ | $\Sigma n$ |
|---|---|---|---|---|---|
| E1.PropertySet1.property = xxx | 3 | 1500 | 1450 | 2000 | 1949 |
| E2. PropertySet2.property = xxx | | 500 | 499 | | |
| E2. PropertySet1.property = xxx | 2 | 5000 | 4250 | 5000 | 4250 |
| E1.PropertySet2. property = xxx | 1 | 225 | 200 | 3657 | 3560 |
| E2. PropertySet3.property = xxx | | 3250 | 3200 | | |
| E2.QuantitySet1.Quantity = xxx | | 75 | 60 | | |
| E3.QuantitySet1.Quantity = xxx | | 125 | 100 | | |

Once calculated, the values (quantified indications) in Table 3 are converted into a measurement outcome ($RI_{Structural}$). Our measurement outcome has two parts, an 'Overall Score', and an 'Individual Score'. The Overall Score is the percentage of the total number of correctly translated IFC elements weighted by the corresponding $ri_d$ values. Since the overall score is weighted by the $ri_d$ value, an inaccurate translation of a more important IFC element (with $ri_d$ value of 3) will reduce the overall score more, compared to that in a lesser important IFC element (with $ri_d$ value of 2 or 1). The Individual Score is the percentage of the total number of correctly translated IFC element under each $ri_d$ value. These scores are calculated using the measurement model represented by equations (1) and (2). The equations are used to calculate the scores for each discipline separately.

$$Overall\ Score\ (RI_d) = \left[\frac{\sum_{i=1}^{ri=3}\left(\frac{\Sigma n}{\Sigma N} \times ri_d\right)}{\Sigma ri_d}\right] \times 100 \qquad (1)$$

$$Individual\ Score = \left[\frac{\Sigma n}{\Sigma N}\right] \times 100 \qquad (2)$$

Where:

$\Sigma N$ is the sum of the total number of IFC elements tested during the conformance test, grouped by the type of IFC element and the assigned $ri_d$ value.
$\Sigma n$ is the sum of the total number of IFC elements correctly translated during the conformance test, grouped by the type of IFC element and the assigned $ri_d$ value.
$ri_d$ is the relative importance value assigned to corresponding IFC elements.

The measurement outcome calculated using the measurement model will be displayed in the format shown in Figure 1. The top-right cell denotes the discipline for which the measurement outcome is calculated. The left column shows the Overall Score. The values below High, Med, and Low, show the Individual Scores under the corresponding importance level. These individual scores represent the ‘interoperability level’ which conveys to end-users the percentage of accurately translated IFC elements under each importance level during the conformance test. The proposed format abstracts away all the complications of the interoperability measurement process and represents the results in a simple manner that could be easily understood by the end-users. The format is designed in a manner that could be displayed along with the IFC certification logo so that end-users can clearly understand the current interoperability level and the limitations of the accuracy of translation of the BIM software tool that was tested for conformance. This format could be used as a standard method to represent the outcome of any interoperability measurement tests that generate measurement results in the manner shown in Table 2; thus enabling the end-users to compare the interoperability level of one BIM software tool to another, even though the interoperability measurement could be conducted by different bodies.

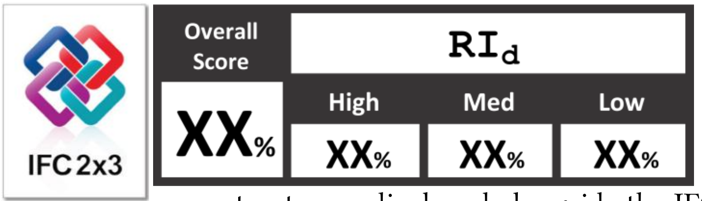


Figure 1: Proposed measurement outcome displayed alongside the IFC logo

For clarity on how the measurement model converts the quantified indications into measurement outcome, the steps required for the calculation is demonstrated for $\mathrm{RI}_{\mathrm{Structural}}$ (data referenced from Table 3).

Individual Score for $\mathrm{RI}_{\mathrm{Structural}}$ for $\mathrm{ri}_{\mathrm{d}}$ value '3'

$$= \left[\frac{\Sigma n}{\Sigma N}\right] \times 100 = \left[\frac{1949}{2000}\right] \times 100 = 97.45\%$$

Individual Score for $\mathrm{RI}_{\mathrm{Structural}}$ for $\mathrm{ri}_{\mathrm{d}}$ value '2'

$$= \left[\frac{\Sigma n}{\Sigma N}\right] \times 100 = \left[\frac{4250}{5000}\right] \times 100 = 85\%$$

Individual Score for $\mathrm{RI}_{\mathrm{Structural}}$ for $\mathrm{ri}_{\mathrm{d}}$ value '1'

$$= \left[\frac{\Sigma n}{\Sigma N}\right] \times 100 = \left[\frac{3560}{3657}\right] \times 100 = 97.34\%$$

Overall Score for $\mathrm{RI}_{\mathrm{Structural}}$ $= \left[\frac{\Sigma_{i=1}^{ri=3}\left(\frac{\Sigma n}{\Sigma N} \times ri_d\right)}{\Sigma ri_d}\right] \times 100$

$$= \left[\frac{\left(\frac{1949}{2000} \times 3\right) + \left(\frac{4250}{5000} \times 2\right) + \left(\frac{3560}{3657} \times 1\right)}{(3+2+1)}\right] \times 100 = 93.28\%$$

The result of the calculation could be displayed as shown in Figure 2

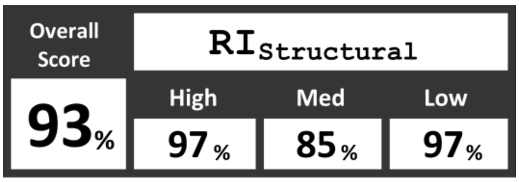


Figure 2: $\mathrm{RI}_{\mathrm{d}}$ for the Structural discipline

Using the same principle, $\mathrm{RI}_{\mathrm{Interior}}$ , and $\mathrm{RI}_{\mathrm{Plumbing}}$ are calculated and shown in Figure 3 and Figure 4, respectively.

| Overall Score | $RI_{Interior}$ | | |
|---|---|---|---|
| | High | Med | Low |
| 90% | 88% | 90% | 97% |

Figure 3: $RI_d$ for the Interior discipline

| Overall Score | $RI_{Plumbing}$ | | |
|---|---|---|---|
| | High | Med | Low |
| 88% | 80% | 99% | 91% |

Figure 4: $RI_d$ for the Plumbing discipline

Even though the outcome of the round-trip tests (Table 2) used for calculating the $RI_d$ was the same, the measurement outcome clearly shows that there are noticeable differences in the interoperability levels for each discipline. The end-users from each discipline now can understand what the results mean from their perspective, for the data exchanges done using the BIM software tool that was tested. The measurement outcome can be interpreted as follows: the BIM software tool that was tested is better suited for data exchange in the Structural discipline because 97% of the most important IFC elements needed for the Structural discipline were translated accurately. The support of the BIM software tool is not as strong for the Plumbing discipline. Even though the medium and low importance IFC elements in plumbing discipline show high accuracy, the high importance IFC elements related to plumbing discipline are only 80% and may show inaccuracies while doing a data exchange. Hence, with this measurement outcome, the stakeholders in these disciplines can take an informed decision whether to go ahead or not with the current data exchange or wait till the vendors to update the translator modules of the BIM software tool or look for another tool.

As for software developers, they could refer to the $ri_d$ result data in Table 3 and could make a priority list of IFC elements that are of high importance, and can focus on correcting the errors associated with those elements first. They could rerun the conformance test to check whether the percentage accuracy has increased after a bug fix, if the value is not increasing, it may indicate that the latest bug fix might have introduced other errors with other IFC elements. Thus, the proposed format can provide clear insights for software developers on which errors are to be corrected first and what effect those corrections cause to the system as a whole.

## 5 CONCLUSION

Using a mechanism to segregate IFC elements according to their relative importance with respect to various disciplines enables new dimensions in handling the complexities of the IFC data model for interoperability measurement. The proposed $RI_d$ framework demonstrates the possibility of viewing IFC elements from the perspective of the end-user in various disciplines to allow them to focus only on what is relevant to them. It also enables the representation of conformance test results in a segregated manner relevant to each discipline. The standardised format to represent the measurement outcome enables one-to-one comparison of the interoperability levels of different BIM software tools on a standard scale. It can also serve as a gauge for the software developers to analyse the progress of their efforts to rectify the translator errors. Also, a standardised measurement outcome will enable the customers and the vendors know how accurate their software tools are as compared to other competing software tools. This could be a self-motivation or a 'forced' motivation for vendors to improve the accuracy of their translators.

This paper serves as a starting point of the research on the subject of the relative importance of IFC elements, and reports on the basic functionalities of a mechanism for segregating IFC elements as per their relative importance for various disciplines. A limitation of this work is that the sample implementation of the $\mathtt{RI_d}$ framework has only demonstrated the theoretical implementation and does not assign $\mathtt{ri_d}$ values to real IFC entities. Further research is being conducted by the authors to develop an improved conformance test methodology which incorporates the $\mathtt{RI_d}$ framework.

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# VALIDATION AND INFERENCE OF GEOMETRICAL RELATIONSHIPS IN IFC

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**Abstract:** The Industry Foundation Classes are a prevalent open standard to exchange Building Information Models. In such a model, geometric representations are provided for individual building elements along with semantic information, including a significant amount of properties related to geometry and explicit topological relationships. These relationships and quantities introduce redundancies and often inconsistencies as well. Moreover, they introduce complexity in down-stream processing. Combining multiple aspect models into a single model has non-trivial consequences for the connectivity graphs. Programmatic mutations are complicated because of the relationships that need to be updated as a result of changes.

In order to alleviate these issues, this paper provides a theoretical framework and implementation for both validating and inferring semantic and topological constructs from the geometric representations, rooted on Egenhofer spatial predicates and extended with the IFC modelling tolerance. Combining these two concepts, wall connectivity is equivalent to the intersection of the wall representation boundaries, where a boundary is not a surface, but rather a hollow solid with a thickness derived from the modelling tolerance.

The algorithms presented in this paper are implemented in fully open source software based on the IfcOpenShell software library and the CGAL computational geometry library using Nef polyhedra. We provide a formalization of space boundaries, spatial containment and wall connectivity relationships. The validation and inference rules are applied to a public set of building models. We conclude that exported models have geometric flaws and that several relationships can indeed be inferred by means of generic geometric intersection logic.

**Keywords:** BIM, IFC, Geometry, Validation

## 1 INTRODUCTION

### 1.1 Industry Foundation Classes

The Industry Foundation Classes (IFC) are a prevalent open standard to exchange Building Information Models (BIM). In such a model a geometric representation is provided for individual building elements along with user-extensible and multi-disciplinary semantic information. The geometrical definitions by which representations

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can be constructed are derived from existing standards for exchanging Computer Aided Design (CAD) geometries and enriched with domain specific parametric cross section profile definitions and more. Coming to a full evaluation of the building element geometries requires a considerable software implementation effort and is computationally intensive due to complex sweep operations and Boolean operations.

In order to make those models useful to a high number of applications, a significant amount of properties and explicit topological relationships are provided by the IFC authoring applications (see Figure 1 for a hierarchical overview of all IFC relationships). These include spatial containment relationships, wall connectivity relationships, space bounding interfaces and quantities for surface areas and volume. It is essential these to be explicitly specified, in particular for importing data into applications that are unable to evaluate computational geometry, for example spreadsheet-based facility management applications. On the other hand, simulations and interoperability with Geographical Information Systems (GIS) may pose strict requirements on geometric and topological validity. For example, boundary interfaces are vital for thermal simulation (Bazjanac 2010) and connectivity information is vital for evacuation analysis. Without this information these analyses cannot be executed directly on BIM data.

However, these explicit relationships and quantities by their nature introduce redundancies between the semantic and geometrical constructs and often introduce inconsistencies as well. Moreover, they introduce further complexity in downstream processing of IFC building models. In particular, combining multiple aspect models into a single model has non-trivial consequences for the connectivity graphs if such relationships are not well stated and understood. There is also a fundamental problem with these relationships and the file-based nature of data exchanges in the industry. First of all, IFC (due to the EXPRESS legacy) are essentially information silos, references can be made within a file, but not easily to other files. The usage of aspect models (subsets of the overall model relevant to a specific discipline) is essential in industry to allow practitioners to use bespoke software for their expertise. Therefore, the amount of relationships that can be expressed when using aspect models is limited to only the elements in scope of that discipline. To exemplify: when one aspect model contains the spaces and another aspect models the walls and slabs, it is impossible for an authoring tool to provide the space boundary relationships.

While traditionally information exchanges in the construction industry have been predominantly file-based, more and more initiatives arise that aim to exchange incremental model subsets, partial exchanges or do content negotiation based on the possibilities of the importing and exporting side. These more interactive and collaborative exchanges are considered part of the higher BIM levels 1 and 2 in industry. Examples of this are the BIM Collaboration Format (BCF) BIM Snippet (see Lindhard and Steinmann (2014) for example, that advocates transferring isolated elements because of the dense relationship graphs otherwise) and the OpenCDE API[6]. These kind of incremental exchanges, additions and modifications are much easier on a "bag of elements" model, similar to a dataset of GIS features, where relationships are not stored explicitly but computed on the fly where needed.

[6] https://github.com/buildingSMART/OpenCDE-API


Figure 1. Hierarchical overview of relationships in the schema. IfcRel- prefixes have been removed for brevity. Many are related semantic constructs such as IfcRelDefines subtypes. A significant amount of the IfcRelConnects subtypes are related to proximity, containment and neighborhood and can likely be geometrically inferred.

## 1.2 BIM and computational geometry

Geometry is not the only aspect conveyed in BIM models, but it’s an important part and one of the most complex parts of the schema. Many issues with interoperable IFC usage stem from geometrocal issues, as indicated in literature (Feringa and Krijnen 2015; Arroyo Ohori et al. 2018; Solihin et al. 2015). Also, many of the challenges on multidisciplinary usage of BIM models are related to geometry, such as conversion to CityGML and thermal analysis.

The geometry resources are one of the largest and more complicated subschemas of the IFC specification. In the current IFC4X1 schema there are 153 subtypes of IfcRepresentationItem and 22 subtypes of IfcProfileDef. This indicates the implementation effort required to implement full geometric support for the IFC schema. Most of these geometric definitions are derived from ISO 10303 42, but over time bespoke extensions have been added, such as the domain-specific parametric profile definitions, tapered extrusions and revolutions and more efficient ways to encode tessellations and piecewise connected curves.

In addition to the amount of geometry definitions, for the purpose of this research, the most influential characteristic is the implicitness of the geometry definitions. In contrast, many GIS standards use explicit representations where (maybe besides a transformation for the Coordinate Reference System) the eventual location and shape of the feature can be read from the data without much computation. Instead, IFC has a placement hierarchy that matches the project decomposition structure so that every element geometry is defined within its own Local Coordinate System. Furthermore, there is an extensive amount of processing required for sweeps and Boolean operations, defined in a typical IFC file, to be visualized.

A typical IFC file contains individual solid volume geometries for the respective building elements. However, for other use cases, such as thermal simulation, another view on geometric data is required where pairs of neighboring spaces are connected by means of a single thin-walled interface. Provisions for this are incorporated in the IFC schema by means of the IfcRelSpaceBoundary (a subtype of IfcRelConnects).

There are various geometric models that can be used underlying an implementation of the geometric resources in IFC. A semantically good match is found in the Boundary Representation (BRep) model. It consists of a hierarchy of topological entities: Solid > Shell > Face > Loop > Edge > Vertex. Face, Edge and Vertex have associated geometric components: an underlying Surface, Curve and Point. At every level a tolerance factor is applied so that, for example, a Vertex point can be some small distance away from the Edge curve that is connected to the Vertex. This tolerance is necessary because floating point arithmetic on modern computer hardware is intrinsically imprecise. The tolerance value is also necessary because some solutions to geometric intersections are inherently imprecise. When operations are applied to BReps the tolerance increases as the uncertainty of the operands is added together. This can result in situations where the tolerance value is on the same scale as the geometric detail and a consistent separation between interior and exterior is no longer provided by the boundary. The shape has then become invalid. This will likely happen when chaining many operations or when using many operands. An open source implementation of the BRep model and associated algorithms can be found in Open CASCADE[7]. IfcOpenShell[8] is a software library that implements support for the geometrical resources in IFC and is based on Open CASCADE.

Other implementations of IFC operate internally on triangle meshes or polyhedra. CGAL (Fabri et al. 2000) is a software library for computational geometry that offers higher precision number types that are implemented in software. In addition, by restricting operands to polyhedra, it's possible to guarantee exact constructions. Nef polyhedra (Bieri and Nef 1988) are closed under Boolean set operations, which is not the case for the BRep model described above. Hence, further processing on Nef polyhedra in CGAL is much more robust and precise. This at the expense of less direct implementation available for the kind of advanced sweep primitives in IFC and curved surfaces can be represented only as faceted approximations.

## 1.3 Structure of this paper

In the following section, the current state of the art with respect to validation and geometrical processing is outlined. Following that, we provide a formalization of spatial containment, wall connectivity and space boundary relationships. The validation and inference rules are tested on a public set of building models and the results are listed. A

7 https://www.opencascade.com/
8 http://ifcopenshell.org/

conclusion is provided that reflects on the presented work and provides an outlook for further research.

## 2 State of the art

A theoretical framework for assessing the validity of an IFC file is provided in Solihin et al. (2015). It explains how errors are introduced at human modelling, in exporting to IFC and in the importing application. Indeed, geometrical and topological errors are referenced as a main source of errors in IFC files and the research includes several examples encountered in models. It does not provide a geometrical formalization of these errors.

Within the context of a reinterpretation of IFC data as CityGML models, Arroyo Ohori et al. (2018) discusses how geometrical and topological errors in IFC models impact further automated handling. The focus here was on errors within individual element geometries that are clear violations of the informal propositions in the IFC schema such as non-planar faces and self-intersections of face boundaries and shells.

A framework for validation of GML primitives is provided in Ledoux (2018). The set of geometric primitives in GML is rather different from those in IFC. However, what is included is a check on element disjointedness and containment similarly to how spatial containment is modeled in IFC and geometrical interference is tested on BIM models in practice, using the “clash detection” algorithms widely implemented in BIM-based coordination tools.

An algorithm to automatically calculate second level space boundaries is provided in Lilis et al. (2017) consisting of four stages: (a) parsing, (b) geometry interpretation into a BRep, (c) boundary overlap and (d) boundary projection. Detection and fixes for a set of geometric modelling issues including interfering geometries (clashes), space definition errors where space geometry does not fill the complete bounded area, surface orientation and incomplete shells is provided in Lilis et al. (2015).

Another algorithm to compute second level space boundaries and a conversion to the file format of Open Studio for thermal analysis is provided in El-Diraby et al. (2017). The steps of the algorithm are different from Lilis et al. (2017). In El-Diraby et al. (2017) the solid volumes of the bounding elements are first flattened into thin-walled surfaces and then broken into segments so that a manifold composite solid of space boundaries is obtained.

Egenhofer operators (Egenhofer and Franzosa 1991) find their origin in the GIS domain. They provide a formal approach to qualify the spatial relationship between two geometries as a 3x3 matrix of intersections of the Interior, Boundary and Exterior of both operands. By incorporating the dimensionality (point, line, area) of the resulting intersection this is extended this into the Dimensionally Extended 9 Intersection Model (DE-9IM) (Clementini et al. 1993). While typically applied to two-dimensional geometries, these can be applied to three-dimensional operands as well (Zlatanova 2000) and have been applied to a BIM query interface (Daum and Borrmann 2014).

## 3 Contribution

In this paper we present a generic formalization and corresponding implementation of several geometric predicates to both validate IFC data and infer relationships when missing. The implementation of all predicates is based on the geometric intersection of two operand shapes. In the paper, these are listed based on the increasing order of complexity. The implemented predicates are:

- Containment in building storeys; operates on IfcBuildingStorey × IfcElement. Operand interiors are intersected and the calculated volume of the intersection is computed and compared.
- Wall connectivity; operates on all unique unordered pairs ∈ IfcWall × IfcWall. Intersection is computed on a thin volume around the boundary of the elements and the intersection geometry is projected onto a linear representation of the wall to qualify the connection type (at start, at end, at path).
- First level space boundaries; operates on IfcSpace × IfcElement. Intersection is computed on a volume around the boundary of the elements. The intersection result is flattened into a thin-walled surface and written to the resulting IFC file.

The checks and inferences above are implemented on a novel version[9] (branch) of IfcOpenShell where CGAL is used for geometry interpretation in addition to Open CASCADE. Work on this alternative version started as part of the project described in Arroyo Ohori et al. (2018). The checks are implemented using a Minkowski sum (minkowski_sum_3()) between the interpreted IFC geometries and a padding volume (the current prototype uses a cube with the size of the IFC modeling tolerance, but this is configurable) that is used to convert the surface boundary into a solid. The element to element intersection operation is sped up by finding candidate pairs by an initial bounding box search (box_self_intersection_d()).

## 3.1 Spatial decomposition

The spatial decomposition structure is currently restricted to a tree in IFC. The requirement of a single containing element implies that elements need to be broken up when they are part of multiple building storeys. This does not always match the construction method on site, creates discrepancies between the native and exported model and adds additional complexity to the IFC export process. Therefore, more adaptive assignment to storeys based on preferences by the importing user might be beneficial. The work in this paper can be explained in that regard.

An IfcBuildingStorey does not typically have an associated representation, so a solid volume has to composed based on the 'IfcBuildingStorey.Elevation' attribute. A solid volume (represented as a point set $\langle x, y, z \rangle$ defined in the Cartesian coordinate system of the model) representing the storey envelope is composed, infinite in X and Y directions and bounded over the Z-axis according to definition (1) below:

$$v_{storey} := \langle x, y, z \rangle \ if \ (z \geq storey.Elevation - 0.3m \lor is\_first(storey)) \land (z < next(storey).Elevation + 0.3m \lor is\_last(storey)) \#(1)$$

Where next(), is_first() and is_last() are based all IfcBuildingStoreys in the model, sorted based on their Elevation attribute.

Since storey elevation is typically set at the top of the finished floor height and the floor slab underneath is to be included in that storey we have set 0.6m vertical overlap

9 https://doi.org/10.5281/zenodo.3633653

between the deduced building storey volumes. Storey containment relationships are marked invalid when there is another building storey shape with a larger total overlap with the element shape.

## 3.2 Wall connectivity

Wall connectivity information in BIM models describes how walls can move with respect to each other and how the wall layers in case of a compound structure are folded to provide a watertight shell. Wall connectivity can be useful to find cycles of connected loops and the spaces that bound them, but since spaces can be modelled explicitly and metadata can be attached only when modelled explicitly, there is little use for deriving space geometry from bounding wall cycles. See Fig. 2 for a graphical representation of how the spatial predicate is implemented.

Fig. 2. Graphical depiction of an example wall connectivity intersection operation with two wall "Body" geometries (rectangular); their respective wall "Axis" (a line from square to pointer arrow head); the computed boundary (dotted); boundary intersections (gray); and projections of boundary intersection indicated as narrow rectangle over extended wall "Axis".

Wall connectivity in IFC is only provided in the Z-plane. The generic intersection approach in this paper will also detect pairs of walls stacked vertically. In that case the intersection volume is a horizontally oriented narrow slab. These cases are filtered by looking at the vertical extent of the intersection volume. Similarly, sometimes wall elements are modelled as a form of covering of other wall elements so that they are touching along their longitudinal face. Also in this case no connection relationship should be written. This second exception is filtered by comparing the surface area of the intersection with the surface area of the operands. When area of intersection is close to area of smallest wall the pair of elements is considered not to be connected.

Note that the current implementation of this check assumes that the wall axis begin and end points are aligned with the body representation. An additional check can be in place to verify this.

## 3.3 Space boundaries

Similar to the wall connectivity check, space boundaries are relationships between elements where there is a geometric intersection between the boundaries of the element volumes. In case of the wall connectivity the candidates were of the same type, in this case however, the check still operates on pairs of elements, but exactly one of the elements need to be a space. In addition, since doors and windows are often a bit inset into the wall surface, they do not directly touch the neighboring space. Because of that, for windows and doors, the opening geometry is to be used instead. Since the opening geometry is often offset a bit from the wall surface to prevent precision issues when applying the Boolean operation, the intersection between wall and opening has to be used to remove this offset. This is currently not implemented yet in the validation prototype. For this paper only wall and slab boundaries are checked and inferred.

In this version of the prototype only first-level space boundaries are implemented. These are relationships between spaces and the elements that bound them. Second-level space boundaries are relationships between pairs of neighboring spaces with a uniform boundary element. In Fig. 3 a graphical sketch is provided of how the functionality in this paper can be extended for second-level space boundaries by using a variable padding derived from wall thicknesses.

The inferred intersection shapes can be written to the file, but have to be flattened into a single surface. The result from the Nef polyhedron intersection is a solid volume.

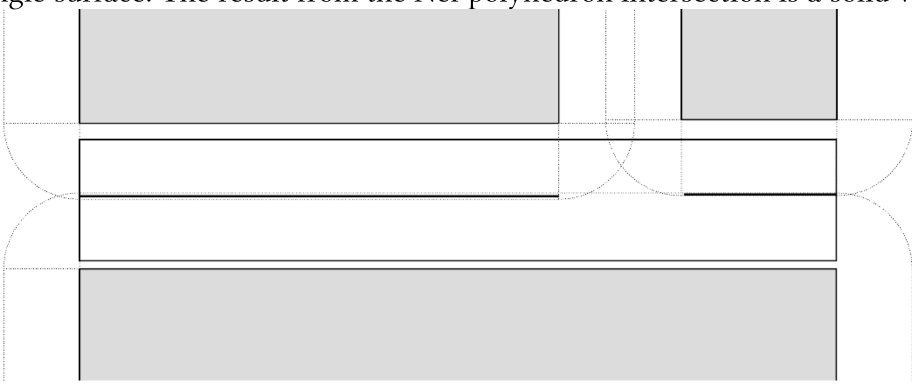

Fig. 3. Inference of second level space boundaries by including half of the thickness of wall elements into the padding operation and computing overlap of padded IfcSpace pairs. Space geometry in solid gray; offset boundaries (dotted); and inferred second level boundaries in black line; Note that this is somewhat speculative as this has not been implemented yet as part of this paper.

# 4 Evaluation

## 4.1 Models

A limited set of IFC building models is assessed for this research, presented in Fig. 4.

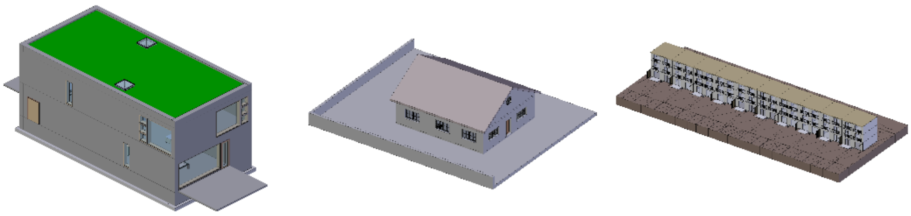

Fig. 4. Three models assessed in this paper: Duplex[1], Fzk[2], and Smiley[3]; [1] IFC2X3; Autodesk Revit Architecture 2011; U.S Army, Corps of Engineers [2] IFC2X_FINAL; Autodesk Architectural Desktop; Automation and Applied Informatics (IAI) / Karlsruhe Institute of Technology (KIT) [3] IFC4; Archicad 20; IAI / KIT

## 4.2 Results

Storey containment. The storey containment check is the most elementary in this paper and also fairly trivial to verify manually by toggling the visibility of building elements storey children in an IFC viewer. If elements are wrongfully located it will likely also negatively impact how the model is handled in the original BIM authoring application, given that these tools often provide a plan-based modelling view to the user. Only the Duplex model reports issues for this check and actually in Solihin et al. (2015) this issue on this exact model is reported as an indication of IFC model quality. The misplaced walls are shown visually in Fig. 5.

Fig. 5. Only the duplex model faces issues with elements assigned to the wrong storey. The two elements are identified by GlobalId 2O2Fr$t4X7Zf8NOew3FL8v and 2O2Fr$t4X7Zf8NOew3FL8v.

Wall connectivity. In Table 1 the results of the wall connectivity check on three models are presented. Three kinds of errors can be detected (a) a connection relation can be missing for neighbouring elements (b) a connection relation can be present but qualified with the wrong connection type and (c) a connection can specified for non-neighboring elements. All these three cases are detected, only the Smiley model was free from errors of this kind. Visual depictions of the cases are presented for the Duplex model in Fig. 6, Fig. 7 and Fig. 8.

Table 1. Wall connectivity errors reported for the three assessed models.

| | Duplex | Fzk | Smiley |
|---|---|---|---|
| missing relation | 2 | 2 | 0 |
| invalid relation: wrong connection type | 4 | 6 | 0 |
| invalid relation: walls not touching | 8 | 0 | 0 |

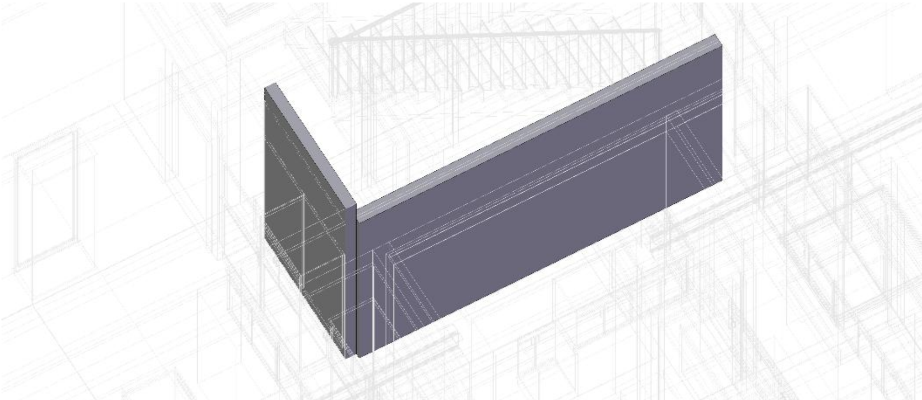

Fig. 6. Example of wall connectivity information in the duplex model where the wrong connection type is supplied. One of the walls is said to be connected ATPATH where both walls clearly touch at their respective begin or end points. The two walls are identified by GlobalId 2O2Fr$t4X7Zf8NOew3FLKI and 2O2Fr$t4X7Zf8NOew3FLKI.

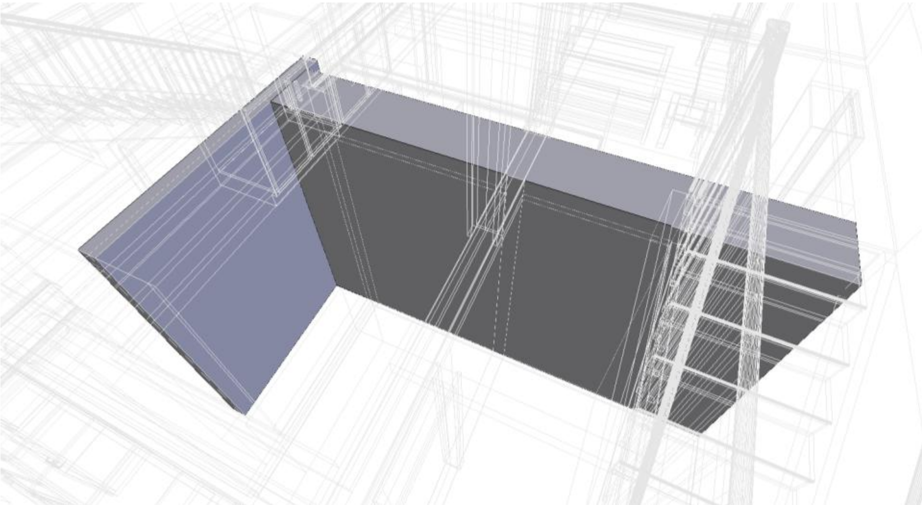

Fig. 7. Example of two touching walls in the Duplex models for which no connectivity information is provided in the model. These two walls are identified by GlobalId 2O2Fr$t4X7Zf8NOew3FKRi and 0iEHWY1$XA8eQeeULq4jDb.

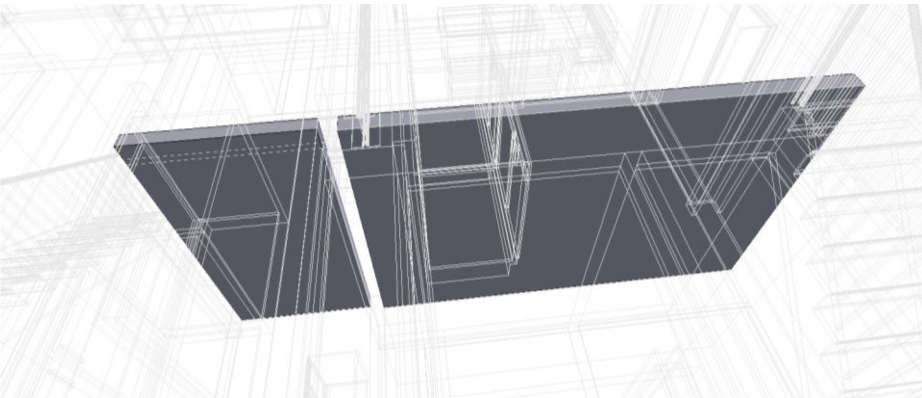

Fig. 8. Example of two walls in the Duplex model that are not touching but for which connection information is provided regardless. These two walls are identified by GlobalId 2O2Fr$t4X7Zf8NOew3FKIu and 0iEHWY1$XA8eQeeULq4jE6

Space boundaries. Space boundary geometry is not typically directly visible in common BIM visualization or coordination platforms. Wrong space boundaries are shown in Fig. 9 for the Duplex model and in Fig. 10 some of the missing space boundaries are located in the Smiley model. The version of the Fzk model used did not have any space boundaries.

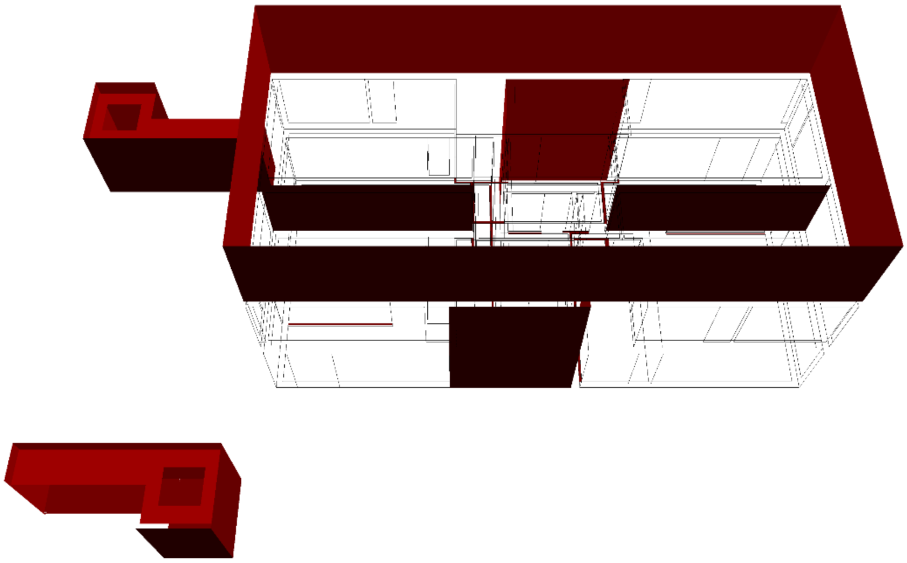

Fig. 9. Wrong space boundary connection geometries in red for the duplex model. Some boundaries are misplaced. Some boundaries do not have the appropriate geometry. Strangely, some space boundary geometry consists of wall footprints.

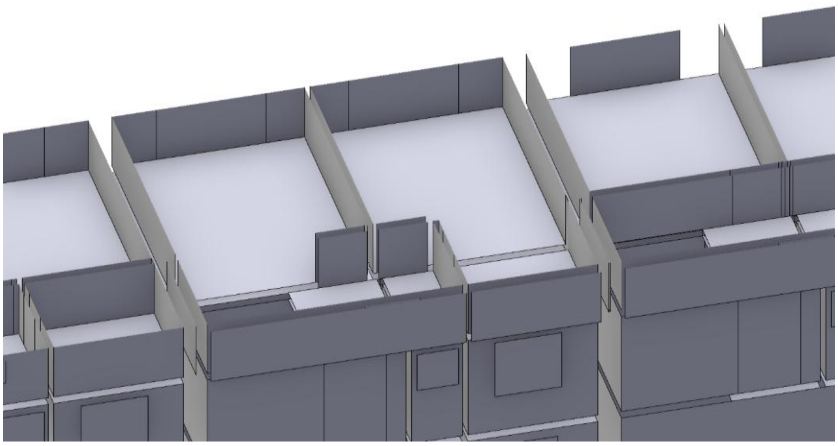

Fig. 10. Visualization of the space boundaries embedded in the Smiley model. The tool developed for this paper reports 10 missing space boundaries, with some of these are located on the exterior (right side of the image); some located on the interior (center)

## 4.3 Performance

Performance optimization has not been part of this initial research prototype. Also, the IFC software library used, IfcOpenShell, favours reliability over performance so quite a bit intermediate validity checks and fixes are applied at the expense of performance on valid input. To give an indication of the processing time in the current state the following times are listed, broken down into the performed steps.

New in the version of IfcOpenShell used in this paper is a two-phase geometry processing routine, where first the IFC instance types are mapped to generic geometrical and topological definitions agnostic of IFC data and afterwards the reinterpretation in CGAL or Open CASCADE happens. These are steps (b) and (c).

Results presented in Table 2 are averages of CPU time on five runs of the wall connection check on the Duplex model on a HP Spectre x360 Convertible 13-ae0xx laptop with an Intel(R) Core(TM) i7-8550U CPU and 16.0 GB RAM on an executable compiled with Microsoft Visual Studio 2017 version 15.9.11 with optimization level /O2.

Table 2. Processing times for the wall connectivity check on the Duplex model.

| Task | Time (s) |
|---|---|
| a. IFC parsing (tokenization and storage) | 0.7174 |
| b. Geometry mapping | 0.0364 |
| c. Geometry creation | 0.5732 |
| d. Conversion to Nef polyhedron | 1.4116 |
| e. Minkowski sum with small cube | 7.0064 |
| f. 3D Box intersection pairs | 0.0006 |
| g. Boolean intersection on Nef | 16.5032 |
| h. Conversion of result back to polyhedron | 1.5342 |

While performance has not been a focus of this initial implementation the timings do show that the current approach of validation adds a significant additional processing time on top of normal visualization workflows where, after (c) and probably a triangulation step, the results can be visualized to an end-user. Since especially the usage of Nef polyhedra adds a significant time penalty, it can be investigated whether regular CGAL polyhedra can be used for the distance query to further reduce false negatives reported by the bounding box intersection. Also, we can investigate whether we can make use of the CGAL simple Cartesian kernel with regular floating-point numbers with full implementation in hardware and only switch to the exact predicates kernel, which is required by Nef, when needed. The Minkowski sum can be eliminated for many geometrical instances when taking the padding into account during construction. For example, an IfcExtrudedAreaSolid of an IfcRectangleProfileDef - which is a very prevalent definition for wall elements - can be constructed with padding by augmenting the rectangle dimensions and extrusion depth.

Note that the geometry generation in (c) only includes wall elements and has opening subtractions disabled (as window and door openings will not impact connectivity). Wall elements are typically simple extrusions that are efficient to process. When evaluating elements with more complicated geometry and openings are included, step (c) will be more significant with respect to the overall processing time of the check and inference computation.

## 5 Conclusion

The aim of this paper was twofold. On the one hand, concretely, a set of validation algorithms has been presented that can be applied to IFC models from practice. On the other hand, we also aim to show that, by providing functionality to infer relationships, a fair amount of the explicit relationships in the IFC schema can be eliminated as they can be inferred using computational geometry. This leads to a lighter schema and a much less dense instance graph in population models. That last notion will help in establishing transactional exchanges of data subsets and interfaces for data extraction and modification.

The validation algorithms show that indeed a fair amount of geometrical relationships are invalid on the limited set of example models. This will not come as a surprise to end-users that are often affected by the limited amount of trust that importing and exporting parties put in the exchanges. This leads to frustration and costly rework. A thorough analysis of building models using a wider set of validation checks will be provided as part of ongoing research.

Further research will be directed at inferring more diverse relationships in IFC. It is believed that the generic approach used in this paper can be applied at additional relationships.

The implementation using CGAL proved to be a useful counterpart to the existing implementation of geometry handling in IfcOpenShell based on Open CASCADE. Further research will be directed at creating a hybrid implementation that can select the most appropriate implementation based on geometry forms and end-user preferences. The performance overhead of running the checks is currently significant, but, by incorporating padding during construction and only use Nef polyhedra and the exact kernel where necessary, likely a lot of the overhead can be eliminated.

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# BIM-GIS IMPLEMENTATION FOR REBUILDING AFTER DISASTER: A CRITICAL EVALUATION

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**Abstract:** The emergence of new technologies in the architecture, engineering, and construction (AEC) industries allow decision-makers to gain a great deal of control over every stage of their projects. However, due to the dynamic and fragmented nature of the AEC industry, developing an effective data exchange between AEC professionals and the construction industries is challenging and requires a major effort for bilateral integration. This challenge calls for an integrated approach across several commonly used platforms. As a representative example, this article discusses the viability of integrating Building Information Modeling and Geographic Information Systems (BIM-GIS) to solve problems in the built environment, such as the data-driven disaster-mitigation process. By thoroughly reviewing previous studies, this paper aims to identify the ongoing theme of BIM-GIS integration and highlight gaps in the literature. As a result, the paper presents several recommendations to address these gaps and improve data exchange in the AEC industry.

**Keywords:** BIM-GIS, data exchange, disaster mitigation.

## 1 INTRODUCTION

The fragmented and dynamic nature of the architecture, engineering, and construction (AEC) industries makes it challenging to effectively achieve robust data communication between industry professionals and the construction fields (Isikdag and Zlatanova 2009). However, new technologies offer professionals the chance to obtain much better control over their ongoing projects.

Integration and interoperability between emerging technologies are critical to achieve a better, more efficient outcome. One example of effective data exchange is the integration of Building Information Modeling (BIM) and Geographical Information Systems (GIS;(Song et al. 2017). BIM has been the tool that bridges the interoperability gap between different disciplines involved in a project. Meanwhile, GIS is predominantly used as a tool to extract the geographical information of an area. Its use is not restricted to the AEC industry, so GIS has been used in relatively diverse disciplines, including construction, disaster mitigation, and forest management (Isikdag and Zlatanova 2009). Others include agriculture and natural resources, community and regional planning, and infrastructure and urban facilities management.

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While each platform has different uses, incorporating the data generated by both platforms could yield an extremely detailed and comprehensive image of a project. This process can help AEC professionals address several complexities in their industry, from managing the flow of information between project stakeholders to micromanaging elements of an AEC project. For instance, the BIM-GIS integration can be useful to a facility manager overseeing the location of various assets, as well as managing the energy assessment for each asset (Zhang et al. 2009; Fosu et al. 2015; Song et al. 2017).

With the increased interest in the integration of BIM and GIS, it is critical to map how far current knowledge has progressed. To that end, this study aims to address some of the potential applications of BIM and GIS integration and any gaps in knowledge in the BIM-GIS literature. More specifically, the objectives of the paper include (1) to identify current trends in BIM and GIS research; (2) to report on existing knowledge surrounding the integration of BIM and GIS; (3) to provide a framework for implementation of BIM and GIS in real-world scenarios; and (4) to present recommendations for future studies.

In addition, this paper provides a critical evaluation of BIM-GIS integration for disaster mitigation. This theme was chosen because of the systems' capacities to complement each other. In a disaster-mitigation situation, GIS could provide information on terrain conditions of the disaster area. Meanwhile, BIM would provide detailed information on the buildings and built environment in the area.

By identifying these research trends, solutions can be proposed to pave the way for designing an advanced AEC data exchange.

## 2 Research Trends in BIM-GIS Integration

There have been several studies on BIM-GIS integration over the past years. Researchers identified trends in both technical and applied aspects. To identify these trends, a digital search query of the ASCE library and Automation in Construction was performed. The query yielded 274 publications dated from 2007 to 2018. To examine this trend, 33 publications were selected for review. The analysis yielded several major themes: (1) BIM as a representation and information management tool; (2) data exchanges between platforms in BIM-GIS integration; and (3) GIS for disaster-management tools (Table 1).

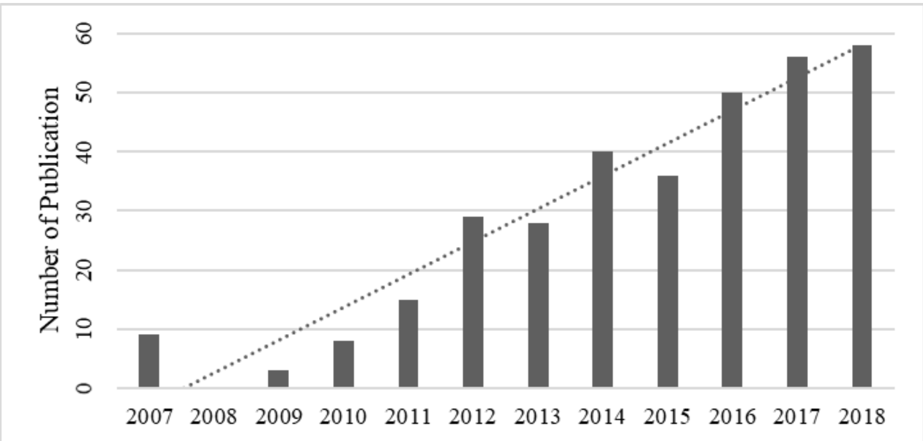


Figure 1. BIM-GIS integration publications between 2007-2018

Table 1. BIM-GIS publication themes from 2007 to 2018

| Themes | Author | Year |
|---|---|---|
| Approaching BIM-GIS technical challenge | Hijazi et al. | 2010 |
| | Kang and Hong | 2016 |
| Automatic data translation from BIM to GIS | Isikdag and Zlatanova | 2009 |
| Benefits of a successful BIM-GIS Implementation | Zhang et al. | 2009 |
| Benefits of BIM-GIS Implementation | Fosu et al. | 2015 |
| BG-ETL software architecture | Kang and Hong | 2017 |
| BIM-GIS data exchanges | Ma and Ren | 2017 |
| BIM-GIS in disaster mitigation | Lapierre and Cote | 2007 |
| | Dollner and Hagedorn | 2007 |
| | Isikdag et al. | 2008 |
| | Chen et al. | 2014 |
| | Amirebrahimi et al. | 2015 |
| | Tashakkori et al. | 2015 |
| | Deng et al. | 2016 |
| | Wu and Zhang | 2016 |
| | Xu et al. | 2016 |
| | Teo and Cho | 2016 |
| | Hu et al. | 2016 |
| BIM-GIS technical challenge | El Meouche et al. | 2013 |
| | Dollner and Hagedorn | 2007 |
| | Isikdag and Zlatanova | 2009 |
| | de Laat and van Berlo | 2011 |
| | Mignard and Nicolle | 2014 |
| | Karan and Irizarry | 2015 |
| Compromises on Current BIM-GIS integration | Song et al. | 2017 |
| | Ma and Ren | 2017 |
| Data exchange between BIM and GIS | Yuan and Shen | 2010 |
| IFC and City GML role in BIM-GIS integration | Groger and Plumer | 2012 |
| Multiple benefits of BIM-GIS integration | Amirebrahimi et al. | 2016 |
| The importance of data integrity in data exchange | Dollner and Hagedorn | 2007 |
| | Isikdag and Zlatanova | 2009 |
| | El Mekawy and Osmtman | 2010 |
| | El Mekawy et al. | 2011 |
| | de Laat and van Berlo | 2011 |
| | El Mekawy et al. | 2012 |
| | El Meouche et al. | 2013 |
| | Mignard and Nicolle | 2014 |
| | Chen et al. | 2014 |
| | Kang and Hong | 2015 |
| | Fosu et al. | 2015 |

Researchers found that disaster mitigation is one of the more popular themes in recent publications, whereas other publications also partially covered disaster management.

# 3 KEY STRENGTHS OF BIM AND GIS

## 3.1 BIM as a Representation and Information Management Tool

BIM refers to the first building-depiction system targeting both digital transformation and visualization of building components (Eastman et al., 1974). National BIM Standards Purpose (NBIMS 2006) defines BIM as a digital representation of a facility that can display its physical and functional characteristics simultaneously. Although Van Nederveen and Tolman (Nederveen and Tolman 1992) first suggested the term "BIM" in 1992, it did not become popular until the early 2000s, when Autodesk, Bently, Graphisoft, and CAD applications became pervasive (Autodesk Inc. 2003). Furthermore, as the level of development and detail plays a critical role in BIM visualizations, the progress of BIM models from the lowest 2D Level of Development (LOD) to the highest BIM LOD (with 3D models and related non-geometric information) started to accelerate (Bedrick 2013; Fai and Rafeiro 2014).

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## 3.2 BIM as a Multi-dimensional Model

BIM is mostly used in large and complex projects because it integrates the management of several project dimensions (e.g., cost, time, and environmental influences), in addition to the 3D representation of the building. Because of these added dimensions, BIM introduced the concept of 4D, 5D, 6D, and 7D BIM, in which the dimensions of time, cost, sustainable components, and facility-management lifecycle, respectively, are considered (Ikerd 2010; Smith 2014). The various dimensions of BIM require project stakeholders to work consistently and productively, so each dimension can be managed efficiently (Ponting et al. 2005; Succar 2009).

The capacity to run multidimensional BIM modeling allows for the creation of a centralized data-management system for building information. Since cost, quantity, schedule, and other elements are integrated into the model, stakeholders can then retrieve consistent inforication throughout the building lifecycle.

## 3.3 GIS for Topography Data Management

Augmenting BIM, GIS focuses on the management of topographic data and human-made phenomena based in a geographic reference system (Fosu et al. 2015). The system should be compatible with all digitized spatial or geographical data (Huxhold 1991). GIS is essentially an information system that includes topographic data and human-made phenomena grounded in a geographic reference system (Fosu et al. 2015). A GIS database contains operations for spatially referenced data, which are applicable in various diverse spatially grounded disciplines, such as facility management, agriculture, natural-resource management, public health, and business (Berry 1996), among others. With its versatility as a geographic database system, its main advantages include (Lin et al. 1997; Lemer 1998; Valcik and Huesca-dorantes 2002; Zhang et al. 2009): (1) spatial-analysis functions supporting 3D measurements; (2) facilitation of the identification of buildings; (3) enabling users to analyze and predict the remaining service life; and (4) assessing investments based on GIS multicriteria- evaluation support systems.

## 4 DATA EXCHANGE BETWEEN BIM-GIS PLATFORMS

In terms of data structure, BIM and GIS are considered stand-alone systems. Each has a specialized file format that stores only necessary information, such as the BIM file format, which contains information on building elements and materials. Attempting to develop a file format that encompasses both systems would be too complex because the information must be mapped across each system. In addition, each BIM's and GIS's development mean the respective system's file structure is always updated (Andrews 2019).

Many researchers have investigated how data exchanges between BIM and GIS platforms can be executed. There have been several approaches: (1) BIM to GIS data export; (2) GIS to BIM data export; or (3) BIM and GIS data export to a third platform known as City Geography Markup Language, or City GML (Ma and Ren 2017). City GML is the common standard used in GIS, whereas Industrial Foundation Class (IFC) performs the same role in BIM, which is the leading standard for BIM-GIS integration (Hijazi et al. 2011; Gröger and Plümer 2012; Cheng et al. 2013). However, this conventional approach inadvertently led to the misalignment of data between the BIM-GIS system (Yuan and Sheng 2010). In this respect, Isikdag and Zlatanova (2009a) observed that due to the conceptual misalignment of the BIM-GIS systems, viable data conversion could not be achieved by transferring one dataset to the other one. This limitation can be addressed by using models that not only support both IFC and City GML but also allow bi-directional conversion of data between the two, such as the Unified Building Model (UBM;(El-Mekawy and Östman 2010; El-Mekawy et al. 2011, 2012). To this end, a two-part transformation of the geometric and semantic datasets is required.

In addition to the UBM, there are approaches studied by other researchers to address BIM-GIS technical challenges, including web technology, a semantic-based multi-representation approach, prototype implementation, and a resources-description framework. For example, a study suggested a web platform as a transition between the GIS and BIM systems that visualizes both models (Döllner and Hagedorn 2007). Meanwhile, another study found an approach using a semantic web format allows researchers to query multiple models (Karan et al. 2016).

Researchers also developed programs such as Geo BIM (Berlo and Laat 2011) and the Urban Information Modeling extension to manage facilities (Mignard and Nicolle 2014). Another study introduced a prototype displaying the procedure of interoperability based on existing software (El Meouche et al. 2013). Finally, a number of researchers tried to shed light on this gap by demonstrating conceptual frameworks to transition automatically from BIM to GIS (Isikdag and Zlatanova 2009; Chen et al. 2014). The data-integration solution presented by previous research seemed to focus mostly on a conceptual level. Even though the solutions promised interoperability between them systems, case studies are necessary to investigate their applicability in a real-world scenario. Therefore, the next part of this study presents several cases showing how integration can be implemented.

# 5 BIM-GIS UTILIZATION FOR EMERGENCY AND DISASTER RESPONSE

## 5.1 BIM-GIS-Based Emergency Navigation System

Five articles were reviewed on BIM-GIS integration that focused on emergency indoor-outdoor navigation systems (Tashakkori et al. 2015; Hu et al. 2016; Teo and Cho 2016; Wu and Zhang 2016; Xu et al. 2016). One study combined a building's IFC data with the surrounding environmental data from a GIS to propose an indoor, emergency spatial model (Tashakkori et al. 2015). According to the study, the model serves to improve a responder's awareness of the situation indoors. It is expected that by improving situational awareness, responders could identify the best rescue route in the event of an emergency.

Another study determined a practical algorithm for an optimal evacuation route in a crowded situation (Xu et al. 2016). CAD-BIM data was incorporated into the GIS dataset to develop an algorithm that created an optimized evacuation route inside a building.

Since there has been interest in developing a BIM-GIS-based system to generate an evacuation route, one study sought to shed light on the issue and researchers summarized their contributions as follows (Teo and Cho 2016): (1) developing a framework considering BIM and the Multi-purpose Geometric Network Model (MGNM), based in IFC and indoor networks to display a novel approach to determining the indoor network from IFC automatically; (2) connecting the entrances of buildings and streets by transferring arcs based on indoor-outdoor networks from on a given scheme; and (3) developing a route planning system that is coarse to fine based on both city and building scales.

## 5.2 Integration of BIM-GIS into Disaster Response Systems

BIM models can also be added to map and terrain data from GIS databases to generate a large dataset housed in an Open Geospatial Consortium (OGC) web service. In a disaster, these web services can be used for better disaster management (e.g., selection of sites or designing a field hospital;(Döllner and Hagedorn 2007; Lapierre and Cote 2008; Ma and Ren 2017). BIM-GIS integration could also support construction phases, including disaster-related ones. In general, the advantages of BIM-GIS applications to the built environment are as follows (Song et al. 2017): (1) using data with different spatial scales to discover issues in the built environment; (2) providing comprehensive information on geometry and material of building components by integrating BIM; and (3) enhancing the effectiveness and performance of AEC projects.

# 6 GAPS IDENTIFIED IN BIM-GIS INTEGRATION

Even with the general success of BIM-GIS integration, some uncertainties remain. Most publications that studied their integration did not take full advantage of an independent BIM and GIS. For instance, sometimes, just the visualization of GIS was used, whereas GIS by itself can be used for any geographic decisions with visual content and geospatial modeling. In most occasions, the spatial and spatiotemporal analysis was not explored.

In the publications, some problems with the BIM's generally viable applications and advantages were also discovered. Even though BIM provides geometric and semantic information, the study found that user requirements for information in AEC projects were still lacking. This issue has become more important in recent years as more users are seeking out BIM for the examination of issues such as quality, time, and cost. Another component, such as LOD, is also underused; it has not been considered a spatiotemporal attribute in the integration procedure for the decision-making process.

Notably, in spite of the fact that these elements serve critical functions in GIS, little attention has been given to both spatial and spatiotemporal statistical modeling of GIS and a multidimensional BIM to address knowledge. Unlike construction, the spatiotemporal modeling has been used in several domains (e.g., social science, atmospheric, hydrology, geology, etc.). Spatiotemporal statistical modeling in construction could be used for analyzing different aspects of projects, including quality, progress, safety, contract, coordination, and, especially cost. Considered simultaneously are achieving accuracy and dynamic financial-resource allocation. These are of critical analytical help in the use of holistic, data-driven spatiotemporal modeling, especially examining multiple projects.

Interestingly, there is an enormous potential for a more precise, flexible, or broader use of BIM with GIS integration. For example, it is possible to conduct spatiotemporal statistical modeling in a post-disaster area. This element can be used to analyze the allocation of financial resources in a restoration effort. It would be more efficient than a conventional damage-assessment method, especially if the disaster occurred over a large area.

## 7 CONCLUSION

Despite the extensive topics covered by the literature on BIM-GIS integration, we note here several key areas that have not been fully explored. The integration of BIM-GIS mostly results in compromised data exchange between them. In addition, future studies should address spatiotemporal statistical modeling to measure various aspects of construction projects. The literature review also highlighted several potential uses of BIM-GIS integration studies going forward, including a technology hypothesis, a scientific hypothesis, and a data-source hypothesis. Successful implementation of the hypotheses lies in the extensive data-driven spatiotemporal modeling of AEC projects. The combination of objective analysis and decision making characteristic of BIM-GIS is expected to satisfy the AEC industry's need for future applications.

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# RECOMMENDATIONS TO BIM APPROACH FOR A BRAZILIAN INFRASTRUCTURE COMPANY

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**Abstract:** In recent years, Brazilian government issued a federal decree establishing the National Dissemination Strategy for Building Information Modelling (BIM) with the expectation that BIM will be disseminated in public works by 2028. In addition to this, the Brazilian Association of Technical Standards (ABNT) has set up a committee to generate and disseminate standardization involving the various aspects of BIM implementation. In this scenario, the objective of this paper is to investigate the BIM implementation process in a Brazilian government infrastructure studied company, and to understand how the Design as well the Consultant Firms are facing the new demands about BIM. An exploratory research through qualitative and quantitative approaches was carried out by a case study. The qualitative approach was based on a set of interviews applied with Technical Professionals and the company´s board that work at the studied company. The quantitative approach was held through an online survey questionnaire applied to the designer´s base that work with the studied company. The analysis was also based on five different guides: BIM Project Execution Planning Guide, RICS Guide, CBIC Guide, EUBIM Handbook and European Construction Sector Observatory. As a result, the paper aims to deliver a set of practical recommendations in order to help the studied company define the demands for their designer´s base so that bidding occur in the best possible way, and also to better its BIM implementation process.

**Keywords:** BIM, BIM implementation, Project management, Infrastructure, Civil Construction.

## 1 INTRODUCTION

This paper aims to understand how a Brazilian infrastructure company is implementing BIM in its processes and activities and to understand how the technical contractors (designers and consultants that work for the studied company) have received the new demands from the studied company.

The investigation arose due to the increasing importance and use of BIM in the construction sector and due to the publication of a Federal Decree that institutes BIM implementation in public projects until the year 2028. Also, there are already works in progress of the Brazilian Association of Technical Standards (ABNT) to generate and disseminate standardization involving the various aspects of BIM implementation.

The research method is based on qualitative and quantitative approaches and its result aims to support the studied company to define the BIM demands for their technical contractors accordingly so that bidding occur in the best possible way. Additionally, the

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study aims to support the BIM implementation process improvement of the studied company.

## 2 BIM Implementation in Brazil

In 2018, the Brazilian government issued a Federal Decree establishing the National Dissemination Strategy for Building Information Modelling (BIM), called BIM BR, to promote an appropriate environment for investment in BIM and its diffusion in the country. Among the objectives of this action, there is the intention to diffuse BIM and its benefits, coordinate public sector structuration, stimulate BIM capacitation, encourage competition in the market, develop technical standards, guides and specific protocols for BIM adoption. A BIM BR Strategy Management Committee (CG-BIM) was created to implement the BIM BR Strategy and manage its actions. The expectation is that in 10 years (until 2028) the methodology will be disseminated in public works.

To assist the implementation, the requirements were staggered in three stages:

1. From January 2021: architecture and engineering models elaboration, clash detection, quantitative extraction and generation of graphic documentation;
2. From January 2024: models must include the execution planning of the work, budgeting and models update, and their as built information;
3. From January 2028: BIM implementation in the entire project's life cycle considering post-work activities, management and maintenance services after its completion.

In addition to the government´s actions, the Brazilian Association of Technical Standards (ABNT) has set up a committee to generate and disseminate standardization involving the various aspects of BIM implementation. The Technical Standards include object requirements for modelling, guidelines for libraries and organization, system classification and information management in construction. The aim is to implement these Standards by 2021.

Therefore, both the goals imposed by the government and the development of Technical Standards have set up the movement of Brazilian construction sector towards implementing BIM in public works.

## 3 Method

Qualitative and quantitative approaches were undertaken by a case study using a public infrastructure company located in Sao Paulo, Brazil. According to Yin (2015), the case study helps to understand complex social phenomena in their real-world context, and Martins (2012) states that the act of measuring research variables is the most striking feature of the quantitative approach. Furthermore, Martins (2012) indicates the possibility of combining different research approaches, enabling a better understanding of research problems.

Besides, the literature review, made through the five guide's analysis from different countries and cultures, helped to understand the main recommendations brought by these guides in order to support the BIM implementation in the construction sector of their respective countries or regions.

The qualitative approach was based on structured interviews applied to two technical professionals who support the studied company´s board. The interviews were carried out in July 2019 and intended to understand how the BIM implementation has held and which actions were underway.

The quantitative approach was held through an online survey questionnaire applied in January 2020 to the company's outsourcing base composed by Design and Consultancy firms. The questions were structured on the model presented by Liu et al. (2017), which made it possible to measure the contractors´ BIM maturity. The survey´s aims were to understand how much these firms and their Professionals understand BIM, in which stage their BIM implementation process are and how they have carried out this process. There were 56 contractors contacted from the studied company's base, of which 30 answered the questionnaire. The questionnaire had been available for two weeks.

## 4 BIM GUIDES

Despite the reference to implement BIM within Brazilian context being the CBIC - BIM Implementation Collection for Builders and Developers (2016) collection, in order to base the discussion about the BIM implementation process of the studied company, other five international guides were analysed: BIM Project Execution Planning Guide (2010) from USA, RICS International BIM Implementation Guide (2015) from London, EUBIM Handbook (2016) from European Union, and European Construction Sector Observatory (2019) from European Union.

Specifically about CBIC collection (2016), these guides are part of the sectorial initiative based on the Federal Decree. These guides aim to build common understanding and language around BIM as well to share and promote the consistent introduction of BIM, encouraging wider use of developed standards and common principles, both in national and international levels.

The understanding of Guides' structures and organization allows the analysis and discussion about how Brazil has fomented BIM and how the local companies´ projects have implemented its process as well.

Table 1 shows a summary of the main characteristics of each guide studied.

Table 1: Summary characteristics of BIM Guides.

| | BIM Project Execution Planning Guide | RICS | CBIC | EUBIM Handbook | European Construction Sector Observatory |
|---|---|---|---|---|---|
| Year | 2010 | 2015 | 2016 | 2016 | 2019 |
| Scope | All construction projects | All construction projects | Building construction companies and developers | Public construction projects | All construction projects |
| Origin | Pennsylvania State University Department of Architecture and Engineering, Charles Pankow Foundation, The Construction Industry Institute, The Partnership for Achieving | International BIM Working Group of the Royal Institution of Chartered Surveyors (RICS) - London, including consultants and multinational companies | Brazilian Construction Industry Chamber (CBIC) and the National Service of Industrial Learning (SENAI) | Collaboration between public sector organizations in 21 countries of the European Union | Around 32,000 permanent and contract employees, from 28 countries of the European Union, work in the Commission. These include |

| | BIM Project Execution Planning Guide | RICS | CBIC | EUBIM Handbook | European Construction Sector Observatory |
|---|---|---|---|---|---|
| | Construction Excellence (PACE) | | | | policy officers, researchers, lawyers and translators |
| Objectives | Provide a practical manual that can be used by project teams to design their BIM strategy and develop a BIM Project Execution Plan. It defines structured procedures for implementing the BIM Concept | Highlights international high-level principles around how to implement and use BIM in the design, construction and operation of the built environment, including facets of procurement management and asset management | Develop a clear understanding of BIM applications by orienting its application for construction companies and developers; Clarify, influence and facilitate a common technological platform between all construction stakeholders | Build common understanding and language; Share and promote the consistent introduction of BIM; Encourage wider use of developed standards and common principles | Looks at BIM implementation in the EU, analyses the drivers, opportunities, and challenges, and draws recommendations for EU policy makers and other relevant actors on how to support and foster the adoption of BIM by the construction industry |
| Conceptual approach | Focus on implementation and operationalization of the BIM concept | Focus on giving recommendations to implement BIM, considering its main processes | Focus on application in all project life cycle phases, not only for buildings but also infrastructure and industrial projects | Focus on implementing BIM recommendations at strategic and operational levels | Focus on giving recommendations to foster BIM implementation and digitalization through country case studies analysis |
| Results | The Guide provides a structured procedure for creating and implementing a BIM Project Execution Plan, through four steps:<br>1. Identify high value BIM uses during project planning, design, construction and operational phases<br>2. Design the BIM execution process by creating process maps<br>3. Define the BIM | Provides recommendations for accepted good practice as followed by competent and conscientious practitioners.<br>Gives an overview of BIM as technology, the use of BIM in project delivery and implications of BIM on organizations | It presents first a guide named "The 10 reasons to evolve with BIM" followed by five others guides divided into:<br>1. BIM fundamentals<br>2. BIM implementation<br>3. BIM collaboration and integration<br>4. BIM workflows<br>5. BIM contract types | Policy, strategic and implementation recommendations for introducing BIM to public stakeholders and encouraging its use. Includes General Guidance and Action Recommendations | It brings lessons learnt from case studies in countries across European Union. These lessons learnt include recommendations for all construction value chain, such as BIM policies and instruments; Public procurement; Education, |

| BIM Project Execution Planning Guide | RICS | CBIC | EUBIM Handbook | European Construction Sector Observatory |
|---|---|---|---|---|
| deliverables in the form of information exchanges<br>4. Develop the infrastructure in the form of contracts, communication procedures, technology and quality control to support the implementation | | | | research and development; BIM standardization ; BIM industry initiatives; BIM capacity building and awareness raising; and Establishment of BIM guidelines and standards |

# 5 Field Research

## 5.1 The Brazilian Infrastructure Studied company

The studied company is part of the São Paulo Municipality structure and it is subordinated to the São Paulo City Infrastructure Department. Its operation aims to provide management to projects which are under the São Paulo City Infrastructure Department responsibility. It is a public company and its technical staff is responsible for project management services such as design and construction management followed by assisted operation. The design, consultancy, and construction services are outsourced through a bidding process which follows Brazilian laws.

In 2017 the company's board decided to structure a PMO (Project Management Office) and among its processes there would be a BIM laboratory which first aiming would be the BIM implementation within the company's processes and activities.

Into the PMO structuring context, the first step was to carry out an internal diagnosis to map the current project management processes used by the company, considering the hole company´s process. Based on the process mapping, its comparison with the needed BIM operation process was possible. In the meantime, the company studied and looked to deepen its knowledge about BIM, attending conceptual courses, participating in conferences on the subject as well benchmarking.

The diagnosis answered that the company's biggest issue refers to the scope definition of projects. According to the company's interpretation, the issue was a consequence of bidding information problems, including the Reference Term. In principle, the Reference Term needs to allow a more efficient bidding process. On the other hand, once the projects' scopes had been poorly defined, as consequence, the definition of Reference Terms has usually presented a set of technical lacks which allows serious problems for the bidding processes.

Therefore, based on the diagnosis answer and the BIM implementation goal, an internal understanding of the main expected benefits from BIM implementation was carried out. Among them, the expected benefits are focused on the bidding process, project management, efficiency for design and consultancy contracting process, including the quality increasing of services provided as well as better results about cost, time and quality of the final products; internal team development; increasing the quality of design, including compatibility among systems and solutions; agility increasing on the analysis, including the technical approval aspects into the projects context; improving the relationship with stakeholders; reliable and precise quantitative extraction aiming better quality of costs definition and control; increased agility and transparency in the execution of the construction works; traceability and transparency of information; reduction of contractual additives; to produce models that assist in asset management and maintenance process; to provide assertive compatibility of macro solutions with other companies that have interference in the city (for instance, the light, water and transportation companies); and identify new demands to BIM implementation and BIM process

To achieve these benefits, a list of priority actions was created, which includes the improvement of project's scope process definition; the creation of an information and communication flow suitable with BIM process; the improvement of stakeholder management process, including their management; to contract specialized consultants to assist the BIM implementation process; to provide formal education about BIM and also provide training focused on related tools for the team involved with BIM implementation; to purchase computers and equipment compatible with BIM demands; to purchase BIM software needed to visualize models to extract information and make the necessary projects´ analysis; to create a Standard Book for Contracting (services in general) which describes the biding process considering BIM process; to create a Reference Term for bidding process that will be suitable to BIM process, in which there will be all the specifications of product or service to contract; and carry out a Pilot Project through the application of the BIM Contracting Book and the BIM Reference Term. The expected benefits from each action planned are described in Table 2. According to the description, some of them are in progress while others have not initiated yet and just some of them are completed. The expected benefits from each action planned are described in Table 2.

Table 2: Actions and Expected Benefits by BIM implementation.

| Actions | Status | Expected Benefits |
|---|---|---|
| Improve the scoping process | In progress | More efficient bids.<br>Reduction of contractual additives; |
| Create an information and communication flow for processes including BIM | Completed | Traceability and transparency of information;<br>Increased agility and transparency in the execution of the works. |
| Improve requirements identification process | In progress | More efficient bids;<br>Better relationship with stakeholders;<br>Compatibility of solutions with other companies. |
| Hire consultants to assist the BIM implementation process | To be initiated | Identify new demands to BIM implementation and BIM process;<br>Increased project compatibility. |
| Provide conceptual and tool training to the professionals involved | To be initiated | Team development<br>Better quantitative extraction. |
| Purchase more powerful computers | In progress | More efficient project analysis. |
| Purchase BIM software | In progress | More efficient project analysis;<br>Better quantitative extraction. |
| Create a Standard Book for BIM Contracting | In progress | More efficient bids;<br>Reduction of contractual additives. |
| Create a Reference Term for BIM | In progress | More efficient bids; |

| Actions | Status | Expected Benefits |
|---|---|---|
| bidding | | More efficient contract management;<br>Reduction of contractual additives. |
| Carry out a Pilot Project with the application of the BIM Contracting Book and the BIM Reference Term | To be initiated | Identify new demands to BIM implementation and BIM process;<br>Models that assist in asset management and maintenance. |

Through the course of the actions, the studied company has experienced some difficulties in the BIM implementation, which includes the team's eagerness to model rather than to understand BIM's gains; team does not work exclusively in BIM activities, generating problems of availability and interest; cost constraints of the BIM implementation project; difficulties in complying with existing legislation, once regulatory bodies still require physical project boards to make financial measurements, and; finding a project to use as Pilot for the BIM implementation in the company.

## 5.2 BIM Implementation by Contractors

Based on current discussions about BIM implementation and also taking into account the characteristics of the studied company, an effective strategy to implement BIM through must involve the technical outsourcing parts (design and consultancy firms).

The survey allowed understanding the level of knowledge about BIM of researched firms, how these firms have prepared themselves for the Brazilian Government BIM Decree and how they received the demands about BIM implementation from the studied company.

The survey was a type of controlled one, since it was answered by technically experienced professionals which allows appropriate inferences from the analysis and consideration of survey results. The survey was carried out through a structured questionnaire that was sent in January 2020 which were structured into four parts:

4. 1. Sample characterization;
5. 2. General questions to diagnose the respondents’ knowledge about BIM;
6. 3. Questions about the BIM implementation process;
7. 4. Questions about the respondents' awareness referring to the BIM implementation of studied company.

According to Tables 3 and 4, the controlling promoted on the sample was effective since all survey respondents are technically qualified and have consistent industry experience to answer the questions.

Table 3: Sample Characterization - Educational Profile.

| Educational Profile | Amount |
|---|---|
| Bachelor science (Engineer or Architect) | 14 |
| Master's in science | 8 |
| Specialization in BIM | 2 |
| Specialization in Design Management | 6 |
| Total | 30 |

Table 4: Sample Characterization - Professional Profile.

| Professional Profile | Amount |
|---|---|
| Owner | 13 |
| Junior Designer (1-5 years' experience) | 1 |
| Full Designer (5-10 years' experience) | 2 |
| Senior Designer (More than 10 years' experience) | 6 |
| Others (Managers, Design Prince) | 8 |
| Total | 30 |

The distribution also allows to evaluate the sample as a such of diverse one, from the expertise perspective. It is interesting note the presence of BIM experts into the sample as even they represent the smallest part, their presence indicates a positive way or even some hope about the awareness of Brazilian Construction Industry professionals referring to BIM Education which is one of BIM BR strategy goal. It is interested note that significant part of them are the Firms' Owners or Partners.

About the sample's professional profile, 80% have been working in the construction industry for 10 years or more, as illustrated in Figure 1, 13% are professionals in the intermediate stage of their technical careers and just 3% of sample are from Juniors Professionals community.

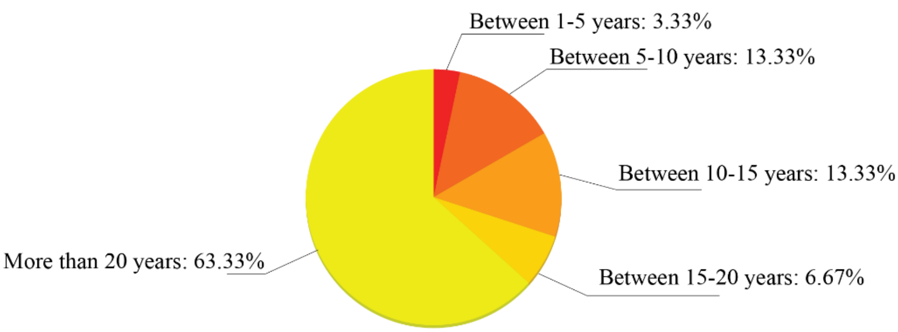


Figure 1: Professional Profile.

Despite the question being a type of multiple choice one, the answers indicated strong expertise in infrastructure projects, including Sanitation and Urban Maintenance, Transport Infrastructure Projects, including special works such as Bridges, Viaducts and Tunnels.

According to Figure 2, the projects developed by the respondents are spread throughout Brazil, South America Countries and in some cases also abroad the continent. Again, the question was the type of multi choice one and despite 70% of respondents indicates acting in Southwest Region, the acting in other regions are balanced.

The concentration of projects in Southwest region is highly associated with their expertise in Sanitation and Urban Maintenance, Transport Infrastructure Projects, once the biggest Brazilian cities are located in Southwest (São Paulo, Rio de Janeiro and Belo Horizonte).

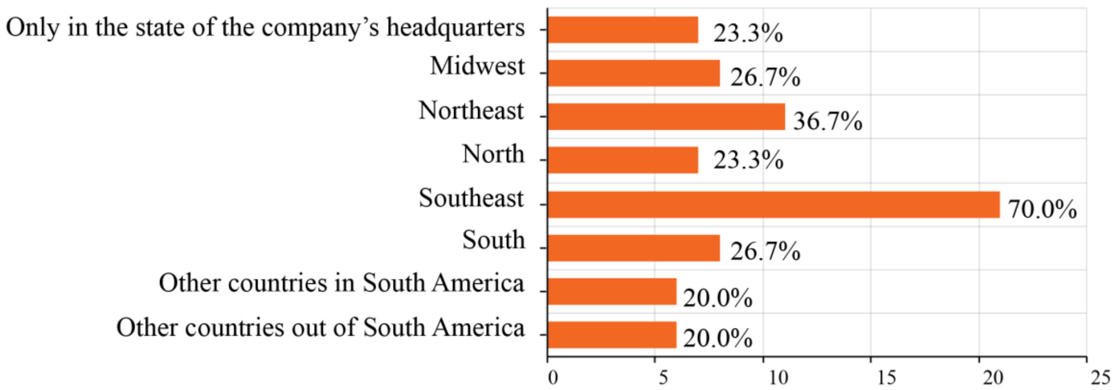


Figure 2: Regions of contractors´ developed projects.

In order to evaluate the respondents' knowledge about BIM, the survey comprised a question focused on the meaning of BIM. It was a multi choice question and according Figure 3, the answers are concentrated in the following meanings: Process of information generation and management; Process focused on produce information to support the Project Management; Process to quantity survey analysis; Set of technologies, process and policies to promote collaboration among the Project's Stakeholders; Application of Modelling Tools; Process for Design Management, including clash; Process for integrated and collaborative design practice .

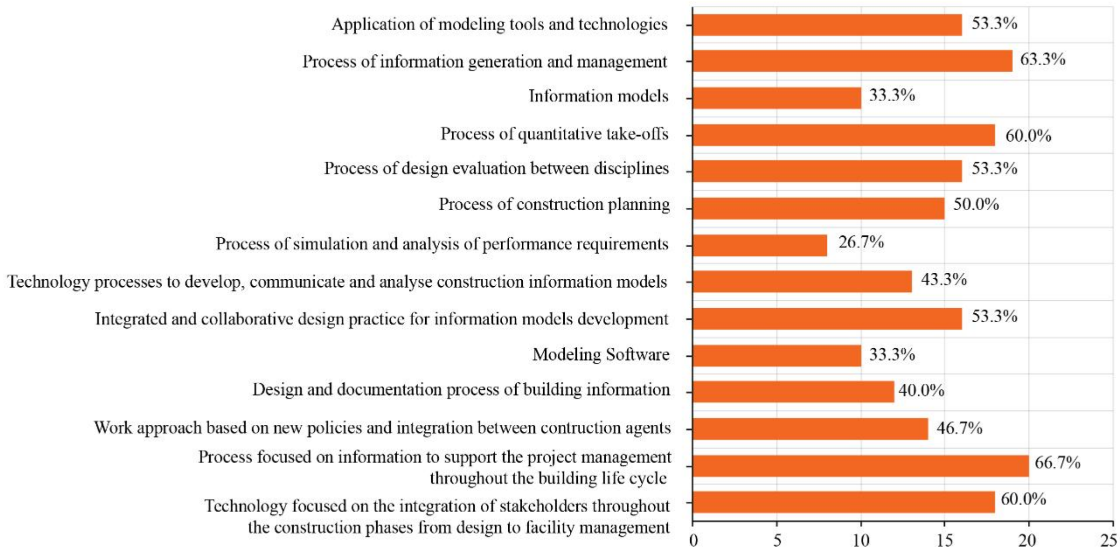


Figure 3: Contractors´ knowledge about BIM.

Regarding the BIM implementation, Figure 4 shows 36,7% of the respondents reported their firms as in an initial phase and 20% is evaluating the possibility of implementing BIM. Among the respondents, 10% is in an advanced phase and 13,3% is not planning to implement BIM at all.

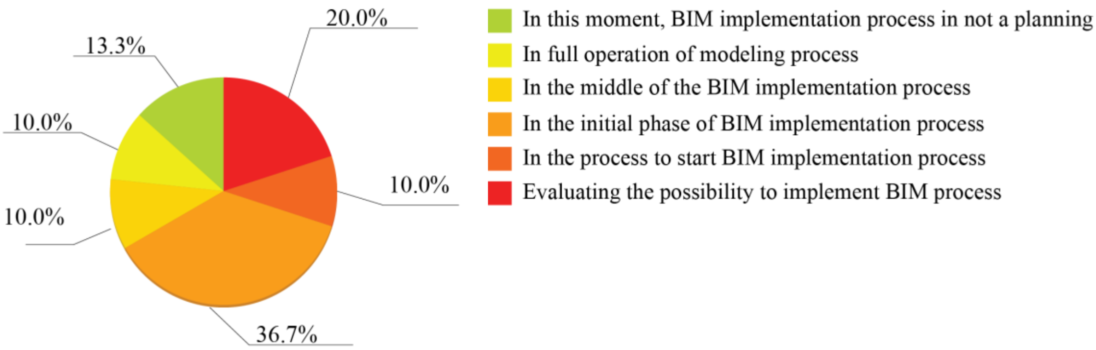


Figure 4: Current contractors` stage in BIM implementation.

The relevance level of actions along BIM implementation process was mapped. The vast majority evaluate the training of the team in BIM software as highly relevant, followed by the understanding about what are the main clients' objectives in relation to modelling. Items such as operational analysis, investments planning, and competences discussion are also questioned and about them, the answers indicated a balanced evaluation.

As the awareness about the BIM implementation process in action of the studied company, which represents a relevant client for the approached contractors, 76,7% answered to be aware. However, the portion which is not aware, represents 23,33%, which is almost the fourth part of total base of outsourcing contractors of the studied company, what indicates the company´s necessity to review the strategy of involvement of their technical contractors in its BIM implementing process.

According to Figure 5, referring to policies and guidelines, the data has indicated as highly relevant the clarifying of new contractual guidelines, the awareness about the information exchange process as well collaboration. Finally, the guidelines for delivering was indicated as equally relevant by contractors.

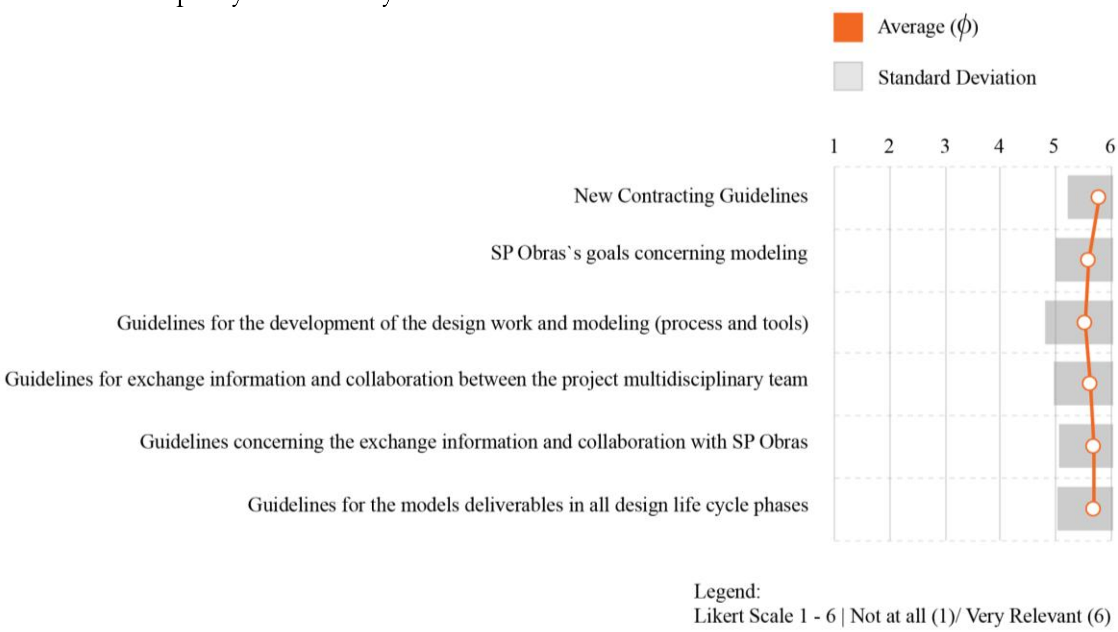


Figure 5: Relevance of clarifications made by the company about BIM implementation.

Regarding the benefits that the BIM implementation can bring, the contractors have put themselves as follows:

- Most contractors believe that: it helps in carrying out the feasibility study and conception of the project; facilitates the analysis and decision-making process; has positive impact on scope definition, project quality and communication; assists the collaboration between project disciplines, anticipating problems and interferences; assists in the quantitative extraction for cost estimates during the design phase; enhances the improvement of operation quality of the projects; and assists in generating as-built documents;
- Most contractors think it has medium relevance: positive impact on project costs and deadlines;
- There was no consensus on the impacts of implementing BIM on increasing the designer's approach to the construction teams.
-

Regarding the challenges that the BIM implementation may bring, contractors have put themselves as follows:

- Most contractors fully agree that: there are difficulties on finding professionals who have the necessary competences for BIM operation or even, training professionals in BIM concepts; difficulties due to the different levels of maturity among the agents participating in the project; difficulties in implementing organizational and cultural changes; difficulties regarding the use of information; difficulty with legal guidelines regarding ownership and production of documentation; resistance to changes in processes of those involved; difficulty in the high cost of implementation; and difficulty in defining contracts based on the concept of information modelling.
- Most contractors partially agree that: it makes it difficult to form project teams; hinders effective collaboration between the parties involved; and makes it difficult to manage the models.
- There was no consensus on the difficulties of implementing BIM on the clear understanding of the responsibilities of each involved.

Regarding to the analysis of the relevance among Technology, Processes and People within BIM implementation process, the majority of respondents consider People the most important aspect, followed by Technology and finally, Process is pointed out as the less relevant aspect as illustrated in Figure 6.

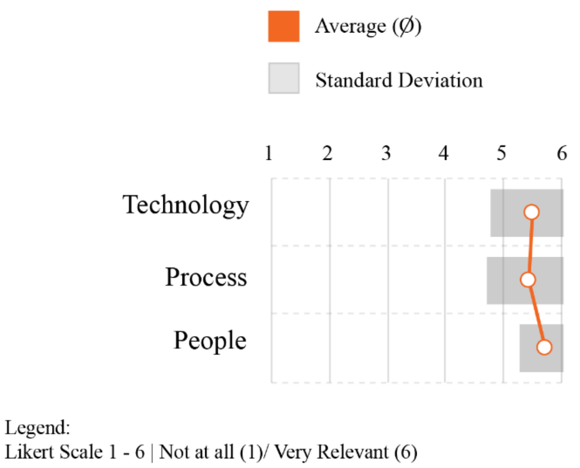


Figure 6: Relevance of Technology, Process and People in BIM implementation.

Specifically about the People aspect, respondents consider the attitude of the contractors and the readiness to practice new workflows, processes and uses of technologies are the most important aspects for the implementation process, as illustrated in Figure 7.

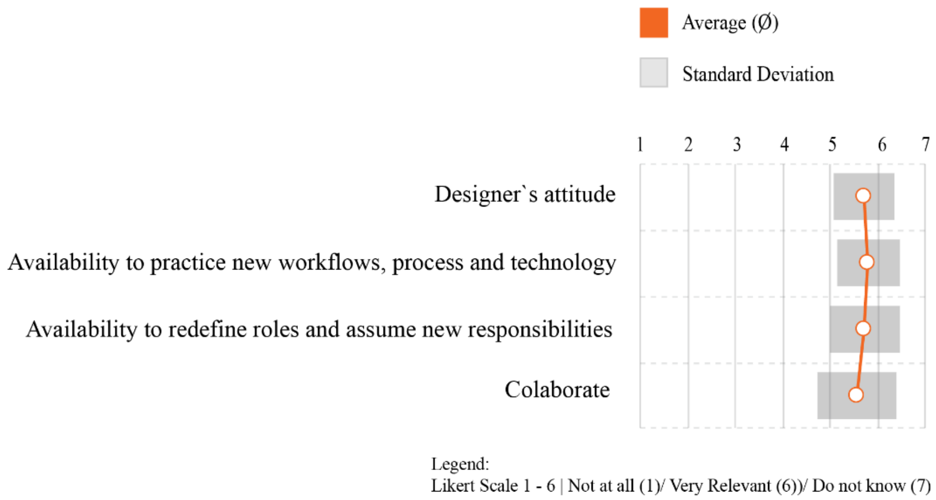


Figure 7: People aspects in BIM implementation.

Within the Technology aspect, Figure 8 indicates that the respondents consider the software functionality, system compatibility, management of model creation, and management of model sharing are the most important aspects that allow implementation process in appropriate way.

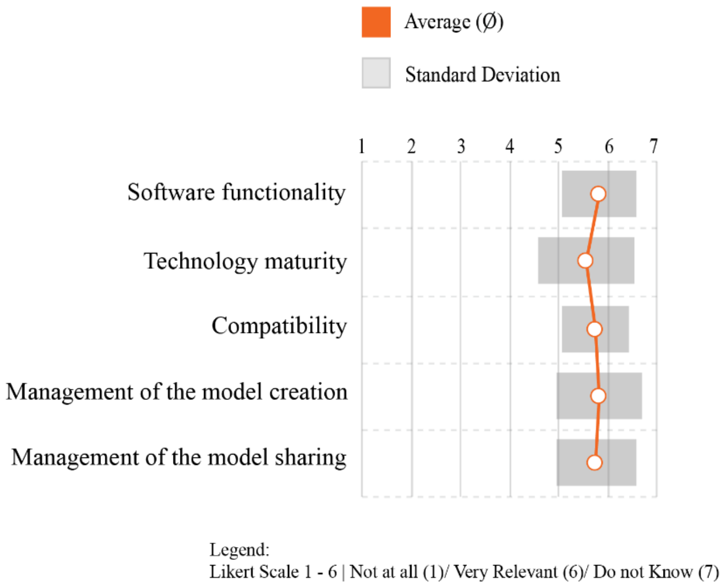


Figure 8: Technology aspects in BIM implementation.

Finally, about the Processes aspect, Figure 9 shows the average of how the respondents consider learning and experience in BIM processes, the format for exchanging information, and collaboration among the agents are the most important aspects.

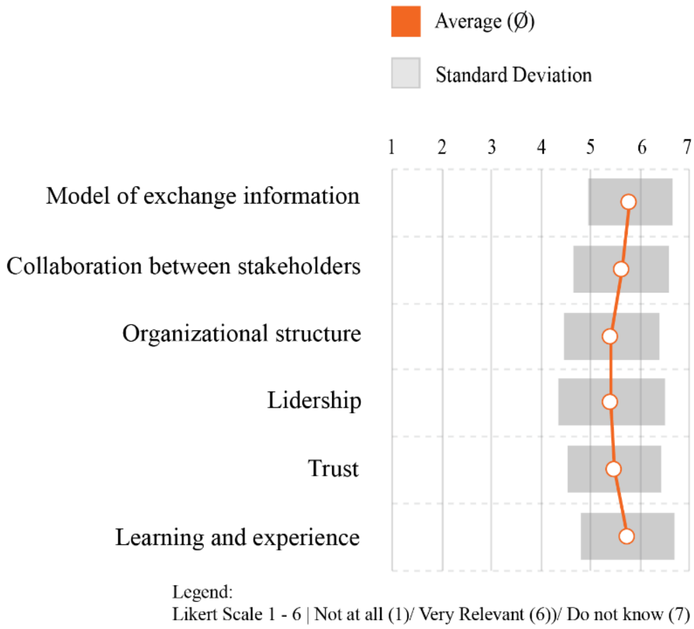


Figure 9: Processes aspects in BIM implementation.

## 6 Discussion

Two sets of discussions were held. The first one is focused on the comparative analysis of the studied company´s actions and the Guides´ recommendations. The second one is based on the comparative analysis of the studied company´s actions and the survey results. From these analyses, recommendations were created for the studied company aiming to improve its BIM implementation.

## 6.1 BIM Implementation: Studied company´s actions and Guides´ Recommendations

The applicable Guides´ recommendations served as a parameter for comparison with the BIM implementation actions in the contracting company previously presented.

For each recommendation, it was assessed whether the studied company already has planned actions that meet that certain recommendation, and if nothing has been foreseen, new recommendations were suggested according the content of Table 5.

Table 5: Recommended actions to the studied company through the Guides´ analysis.

| Guides´ Recommendations | Studied company has planned actions related to the Guides´ recommendation? | Recommended actions to be taken by the studied company |
|---|---|---|
| Make a Business Case | No | Generate a business case for the BIM implementation project, with all the necessary analyzes. |
| Identify BIM goals and uses | Yes | Review goals and uses whenever necessary. |
| Design BIM project execution process* | No | Create a BIM project execution process. |
| Define project`s life cycle phases | Yes | Review project´s life cycle whenever necessary. |
| Define supporting infrastructure for BIM implementation | Yes | Review infrastructure support whenever necessary. |
| Define contract policy | No | Define and disclose contract policy. |
| Define information technology policy | Yes | Disclose information technology policy. |
| Develop information exchange and information needs* | Yes | Disclose information and communication flow. |
| Define interoperability and communication procedures* | Partially | Define interoperability procedures; Disclose information and communication flow. |
| Technology infrastructure needs | Yes | Review technology infrastructure whenever necessary. |
| Define model structure* | No | Define model structure processes. |
| Define project deliverables* | Yes | Review project deliverables whenever necessary. |
| Identify strategies and specific BIM requirements for the hiring process | Partially | Identify strategies and specific BIM requirements for the hiring process; Define and disclose the Reference Term and the Contracting Book. |
| Define delivery strategy | No | Define delivery strategy. |
| Define project budget* | Yes | Review project budget whenever necessary. |
| Establish teams and stakeholder`s role and responsibilities* | Yes | Review teams and stakeholder`s role and responsibilities whenever necessary. |
| Define the quality control of BIM models | No | Define the quality control of BIM models. |

| Guides´ Recommendations | Studied company has planned actions related to the Guides´ recommendation? | Recommended actions to be taken by the studied company |
|---|---|---|
| Develop pilot studies of BIM implementation and goals | Partially | Put into practice the Pilot Project. |

## 6.2 BIM Implementation Understanding: Studied Company x Contractors perspective

In order to understand whether the studied company and its technical contractors are in line about the BIM implementation, a comparative analysis was carried out. The survey results were placed alongside the main actions of the studied company, and the understanding of BIM, the view of the expected benefits and the view of the existing challenges for implementation were analysed.

### 6.2.1 BIM Vision

Regarding the understanding about what BIM is, from conceptual perspective, it is possible to realize that contractors are in line with the studied company's understating, since most respondents identify BIM as a process to generate information models, which must include enough information to support the management of all processes throughout the project´s life cycle.

Also, most respondents understand that BIM enables collaborative work, improves construction management and it assists in obtaining quantities and budgeting for construction. All of those aspects are listed benefits from the studied company about BIM implementation.

Nevertheless, some crucial aspects must be noted in order to review some implementations strategies which tends to impact the relation between the studied company and its technical contractors. For example, the ranking of relevant aspects along the implementation process attains the attention, since two extremes aspects appear as most relevant: Client Centricity as a strategic one and Software Training as operational. Even more worrying, the contractors pointed out the operational aspect (Software training) as more relevant than the strategic aspect.

The information allows to conclude that the contractors do not evaluate the BIM implementation process as a strategic one, although the significant amount investments (time, money, expertise, clients expectations, employee expectations and mainly their competences) involved in this process and probably the conclusion would be associated with the limited vision about how BIM tends to impact on the contractors business model.

According to the survey results, most of the contractors are concerned about the BIM implementation in their own companies, due to the demands of the context and also to provide high level services to their clients, which includes the studied company of this research.

As to balance lacking about the triad People, Process and Technology, since BIM could be defined as a set of technology supported by processes which is operated by people, and therefore the three aspects have equal relevance, the ranking evaluation approached in the question was purposeful in order to evaluate if the respondents are aware about the concepts which is behind BIM. Due to the answers, apparently the approached firms are not totally aware about the BIM concept.

The survey results indicated in Figure 4 show that 67% of approached firms are immersed within the BIM implementation process, independently of the respective stage.

As to a maturity stage evaluation, it requires a set of methodological analysis, but above all, to verify if BIM discussions and its implementation has been part or not of contractors´ agenda.

On the other hand, the survey results indicated an alert to the studied company. One fourth of contractors are not aware about the BIM implementation process in the studied company, and this research analysis indicates how important is to review the communication protocols in order to make all contractors base aware about the BIM implementation process.

In general, from the approached contractors, the survey results indicated concerning to meet the studied company's interests. For example, when the contractors were questioned about the BIM meaning, the answers are in line with the benefits defined by the studied company. From the studied company side, this perceived alignment is an opportunity to get positive results along the implementation process.

### 6.2.2 Understanding of Studied Company's Needs

Regarding the contractors' awareness about the studied company's BIM implementation, it is possible to conclude that the studied company needs to inform how its processes will impact the contracts. The survey results indicate that 73,3% of the respondents have not identified differences in contracting processes due to the BIM implementation, and 86,7% of respondents understand that it is highly relevant clarifying the new contractual process.

For 80% of the respondents, it is very relevant to define the process about the information exchanging and the collaboration process within the project context.

Finally, for 76,67% of respondents, it is highly relevant to understand the guidelines about the models delivering process, mainly about the level of detailing of each design phase and which information must be contained by models. The studied company has not defined the modelling guidelines and also, they have not defined if changes will be promoted on the analysis process of deliverables. This action must be added to the studied company's actions of BIM implementation.

All mentioned aspects must be disclosed through the Reference Term model and the Contracting Book. The studied company must incorporate the issues and expectations pointed out by contractors in this document.

Table 6 summarizes the comparative analysis of the contractor's expectations and the products to be created by the studied company and shows recommended actions to be taken by the studied company in order to align with its contractors and provide a more efficient implementation process.

Table 6: Recommended actions to be taken by the studied company.

| Contractors expectations | Studied company´s products | Recommended actions to be taken by the studied company |
|---|---|---|
| Need to know the differences in the studied company´s hiring processes and contractual guidelines adopted | Reference Term model, Contracting Book, changes in the projects´ analysis | Disclose to contractors products that are being generated in the BIM implementation |
| Need to know how the information exchange and collaboration process will be | Information and communication flow | Disclose to contractors the information and communication flow |
| Need to understand the guidelines on the delivery of | No explicitly cited changes in its process | Define and disclose guidelines on the delivery of the Models for each phase of |

| Contractors expectations | Studied company´s products | Recommended actions to be taken by the studied company |
|---|---|---|
| the Models for each phase of the project cycle | | the project cycle |

### 6.2.3 Benefits Vision

Regarding the benefits that BIM implementation can provide, a comparative analysis was made between the studied company´s understanding and the contractors' understandings, as follows.

Both the studied company and most contractors believe BIM implementation will result on most assertive feasibility study and better quality of project conception. Table 7 summarizes the comparative analysis of the contractors and the studied company´s perception of benefits with BIM implementation.

Table 7: Benefits and recommended actions to be taken by the studied company.

| Benefit | Studied company´s vision | Contractors´ vision | Recommended actions to be taken by the studied company |
|---|---|---|---|
| Helps in carrying out the feasibility study and project conception | According | According | Create a feasibility study process for BIM projects |
| Facilitates the analysis and decision-making process | According | According | Create a periodic project data analysis process, focusing on decision making |
| Has positive impact on scope definition, project quality and communication | According | According | Keep its actions towards improving the scoping process and putting into practice the information and communication flow created |
| Assists the collaboration between project disciplines, anticipating problems and interferences | According | According | Keep its actions to provide conceptual and tool training to the professionals involved and strengthen the vision of collaboration |
| Assists in the quantitative extraction for cost estimates during the design phase | According | According | Keep its actions to provide conceptual and tool training to the professionals involved |
| Enhances the improvement of operation quality of the projects | According | According | Preview the operation quality needs in the scoping definition |
| Assists in generating as-built documents | Not mentioned | According | Define as-built documents generation, receipt and analysis process |
| Positive impact on project costs and deadlines | According | According | Keep its actions towards the positive impacts in costs and time |

### 6.2.4 Challenges Vision

Regarding the challenges that BIM implementation can generate, a comparative analysis was made between the studied company´s understanding and the contractors´ understandings.

Table 8 summarizes the comparative analysis of the contractors and the studied company´s perception of challenges with BIM implementation, if they are aligned, and the recommended actions the studied company can put into practice for a better understanding between both.

Table 8: Challenges and recommended actions to be taken by the studied company.

| Challenge | Studied company´s vision | Contractors´ vision | Recommended actions to be taken by the studied company |
|---|---|---|---|

| Challenge | Studied company´s vision | Contractors´ vision | Recommended actions to be taken by the studied company |
|---|---|---|---|
| Finding or training professionals in BIM knowledge | According | According | Keep its actions to provide conceptual and tool training to the professionals involved |
| Different levels of maturity among the agents participating in the project | According | According | Enhance collaboration and involve stakeholders in its processes definition to help propitiate the sector BIM maturity |
| Implementing organizational and cultural changes | According | According | Create periodic disclosure of actions about BIM implementation in the organization, presenting examples of benefits generated |
| Use of information | According | According | Put into practice the information and communication flow to perceive needed changes |
| Legal guidelines regarding ownership and production of documentation | According | According | Define legal guidelines regarding ownership and production of documentation |
| Defining contracts based on the concept of information modeling | According | According | Create a contract model including BIM needs<br>Keep its actions to create a Contracting Book |
| Resistance to changes in processes of those involved | According | According | Show value gained with the BIM use to those involved |
| High cost of implementation | According | According | Revise and negotiate the budget for BIM implementation, showing value to those responsible for costs |
| Form project teams | Not mentioned | According | Show the value of BIM implementation on team´s daily practices<br>Provide BIM training (conceptual and tools) |
| Manage the models | Not mentioned | According | Create a process for managing models in a collaborative way |

### 6.2.5 Technology, Processes and People

Regarding what contractors believe to be important in terms of technology, pro-cesses and people, Table 9 shows the recommendations.

Table 9: Recommendations about Technology, Processes and People.

| Theme | Items considered important by contractors | Recommended actions to be taken by the studied company |
|---|---|---|
| People | Attitude of the designers and the readiness to practice new workflows, processes and uses of technologies | Share the processes created and decisions made about BIM with the designers, to increase collaboration |
| Technology | Functionality of the software being used | Share with designers the software that will be used to analyze projects |
| Technology | Compatibility of software | Share with designers the software that will be used to analyze projects |
| Technology | Model creation management | Define model structure processes |
| Technology | Model sharing management | Define model structure processes |
| Processes | Learning and experience in BIM processes | Create a collaborative platform for learning and experience sharing |
| Processes | Format for exchanging information | Disclose information and communication flow |
| Processes | Collaboration between agents | Create a collaborative platform for |

| Theme | Items considered important by contractors | Recommended actions to be taken by the studied company |
|---|---|---|
| | | learning and experience sharing |

## 7 CONCLUSIONS

The research aimed to add value for BIM implementation process of the studied company through recommendations based on the Guides´ best practices and also based on the diagnosis obtained through a survey applied with its contractors.

Table 10 summarizes all the recommendations that the studied company should take into account in its implementation process. The recommendations are taking into account that BIM implementation is a strategic process and must be undertaken through an inter organizational manner. In other words, if the technical contractors are not accordingly involved, the implementation tends to fail.

Table 10: Recommended actions to the studied company.

| Recommended actions to the contractor |
|---|
| Generate a business case for the BIM implementation project, with all the necessary analyzes |
| Create a feasibility study process for BIM projects |
| Review goals, uses and deliverables whenever necessary |
| Create a BIM project execution process |
| Create a periodic project data analysis process, focusing on decision making |
| Create periodic disclosure of actions about BIM implementation in the organization, presenting examples of benefits generated |
| Revise and negotiate the budget for BIM implementation, showing value to those responsible for costs |
| Review project´s life cycle whenever necessary |
| Review infrastructure support and infrastructure whenever necessary |
| Define and disclose contract policy |
| Identify strategies and specific BIM requirements for the hiring process |
| Define legal guidelines regarding ownership and production of documentation |
| Create a contract model including BIM needs |
| Keep its actions to create a Contracting Book |
| Disclose information technology policy |
| Disclose information and communication flow |
| Create a collaborative platform for learning and experience sharing |
| Define delivery strategy |
| Define interoperability procedures |
| Define model structure processes for managing models in a collaborative way |
| Define as-built documents generation, receipt and analysis process |
| Define and disclose guidelines on the delivery of the Models for each phase of the project cycle |
| Define and disclose the Reference Term and the Contracting Book |
| Review project budget whenever necessary |
| Define the quality control of BIM models |
| Review teams and stakeholder`s role and responsibilities whenever necessary |
| Keep its actions towards the positive impacts in costs and time |
| Disclose to designers the products that are being generated in the BIM implementation |
| Keep its actions towards improving the scoping process |
| Keep its actions to provide conceptual and tool training to the professionals involved and strengthen the vision |

| Recommended actions to the contractor |
|---|
| of collaboration |
| Enhance collaboration and involve stakeholders in its processes definition to help propitiate the sector BIM maturity |
| Share the processes created and decisions made about BIM with the designers, to increase collaboration |
| Share with designers the software that will be used to analyze projects |
| Show value gained with the BIM use to those involved |
| Show the value of BIM implementation on team´s daily practices |
| Put into practice the Pilot Project |

Some limitations of this work were identified such as the study with only one contracting company and the limited time to receive survey responses from the contractors. However, several opportunities for future works arose, such as analysing a larger number of studied companies; analysing the views of other stakeholders involved in BIM implementation, such as suppliers of material, construction companies, public agencies; and the study of needs for changes in legislation to meet the needs and specificities of BIM.

These studies would also add to the understanding of the factors that can improve the relationship between stakeholders to improve the process of implementing BIM and, consequently, improve the final quality of projects.

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# WHOLE LIFE CYCLE CONSTRUCTION INFORMATION FLOW USING SEMANTIC WEB TECHNOLOGIES: A CASE FOR INFRASTRUCTURE PROJECTS

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**Abstract:** The construction industry is considered to be lagging behind other industries in terms of the technological advancement. One of the main factors is the lack of integration of incoherent and heterogeneous data on a project level. Whilst the adoption of Building Information Modelling (BIM) technologies and processes was aimed to solve integration issues. The interoperability is still a problem to solve, as most information and data fields show inconsistencies in a number of cases. One of the aspects of the problem is that IFC EXPRESS schema is only machine readable, requires extensive mappings, and usually does not support infrastructure domains other than buildings.

This research explores the possibility of utilising Semantic Web Technologies (SWT) to help achieving some of the desired goals of data interoperability and Whole Life Cycle (WLC) information flow. SWT support the creation of comprehensive, layered, shared, human and machines readable, and extendable knowledge repositories dubbed ontologies. The Resource Description Framework (RDF) which forms the core of SWT provides a rather elegant way of modelling datasets, that is, assigning an Internationalised Resource Identifier (IRI) to each class, instance, and property. SWT are ought to provide better information retrieval and inferencing than current systems used in the industry.

The main objective of this paper is to present a framework to demonstrate how SWT can underpin WLC information flow in water infrastructure projects case study.

**Keywords:** BIM, Ontology, RDF, SWT, WLC.

## 1 Introduction

### 1.1 Building Information Modelling (BIM)

Effective collaboration and systems integration are of significant importance in the Architecture, Engineering, and Construction (AEC) industry. The fragmented characteristics of this industry makes it very difficult to fully exploit the benefits of Information and Communication Technology (ICT), in comparison to other industries (Li el al. 2013). For the past three decades, BIM has been evolving to support data integration in the AEC industry (Cavka et al. 2017). BIM is ought to facilitate collaboration among different parties involved in a project, such as architects, engineers, consultants, contractors, facility managers, and owners. This collaboration is ought to be achieved via continual information exchange. According to Pauwels and Terkaj (2016),

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the IFC standard that was developed by BuidingSMART was aimed at supporting data exchange via providing a central "conceptual schema and an exchange file format for BIM data" (IFC4 Documentation 2020). However, the interoperability issue still exists, and it is prominent in the literature. For instance, We et al. (2019) stated that current BIM object databases suffer from the lack of unified classification system of building components, and thus, negatively affecting interoperability. Moreover, Zhang et al. (2018) further supported this argument as they claimed that when working with IFC instance building models—which is the state of the art in the AEC industry—challenges are encountered by industry practitioners when retrieving domain specific information. They claimed that solutions are usually proprietary and vender specific. Also, Godager (2018) stated that to achieve BIM level 3 and beyond, it is important that data are searchable by both machines and humans—though BIM "maturity levels" are no longer promoted, ISO 19650 series—(UK BIM Framework 2020). Hence, product manufacturers are important actors in the process, yet their participation is constrained by the lack of dynamic links with other domains (Costa and Madrazo 2015). This paper explored establishing these dynamic links to facilitate the information flow from product manufacturers, all the way to the asset management software.

In this regard, one area of research that seems promising is Semantic Web Technologies (SWT). SWT are usually used to create ontological models and have become rather prominent in the AEC research community, particularly in the last decade. Zhong et al. (2019) conducted a scientometric analysis on the ontology research within the construction industry from 2007 to 2017. Their results showed that researchers were initially focused on using ontologies in different areas of construction management. However, they concluded that 2016 marked the year after which researchers' focus shifted towards solving interoperability issues across the building life cycle.

## 1.2 Semantic Web Technologies (SWT)

The main concept behind SWT is to provide and connect ontologies, enabling inference on the data level rather than on the schema level (Pauwels et al. 2017), which is expected to also provide smarter querying. Data models are governed by rules, and complicated models would usually have a large number of rules. Indeed, the more rules in a model, the more processing layers are required. That is not the case when modelling with RDF, however, as it was partially designed with this in mind (Allemang and Hendler 2011). The Resource Description Framework (RDF) is a Semantic Web modelling language that is recommended by the W3C (semantic web – W3C 2020). Databases that adopt the RDF format are usually referred to as triple stores. To represent a relational database in RDF, each row, column, and cell would be allocated an IRI, and hence, giving value to the datum itself. A piece of information represented in RDF is known as the subject-predicate-object triple, figure 1. The object of one triple would form the subject of another and so on. This would result in a family-tree-like data or graph data. Using these technologies, different knowledge domains are represented as ontologies. Gruber (1993) defined an ontology as an "explicit specification of a conceptualisation" and Borst (1997) added to this definition, defining an ontology as "explicit specification of a shared conceptualisation". Therefore, an ontology should be formal, sharable, extendable, and reusable by others. RDFS-Plus and the Web Ontology Language (OWL) are modelling languages built on top of RDF, that differ in their complexity, and hence, inferencing capability. According to Allemang and Hendler (2011), there is a trade-off between the complexity of the ontological model and the simplicity of the required queries. A complex ontology, that is a one that has many properties and restrictions, requires relatively simple queries to return the desired results. Whereas a simpler ontology would require longer queries to return the same results. Therefore, the model/ontology must be designed with querying in mind. Nonetheless, Allemang and Hendler (2011) also stated that increasing the model's complexity may make other applications associated with it more complex.

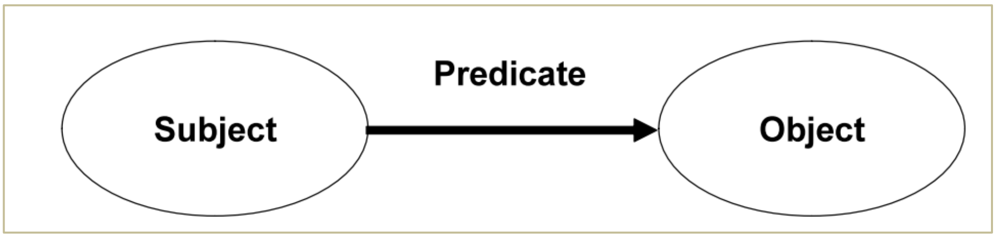


Figure 1: RDF triple

## 2 METHODOLOGY

This paper presents an industry-based research, in which, a major water company in the United Kingdom would act as the subject of the case study (data provider). The water company suffers from the lack of automation in asset data flow from the suppliers to the asset management software. The major issues that this project is ought to solve can be summarised in the following:

- Data modelling and querying.
- Automation of data flow from suppliers' databases to the asset management system.
- Asset management.

Therefore, a literature review was conducted to understand the trends in research on applying SWT in the AEC industry, verify the company's issue as a research problem, and understand the current state of the art and explore some of its current applications. Then, a framework has been developed to tackle these research issues. The methodology for building this framework was adopted from Dawood and Vukovic (2015), who generally classified WLC information flow into four pillars:

1. People
2. Process
3. Policy
4. Technology

The framework in this paper is aimed at the technology pillar, summarised in the flow chart in figure 2, which consists of seven steps. This framework is to investigate the potential of using SWT in solving the problem of data integration, using a WLC of information flow approach.

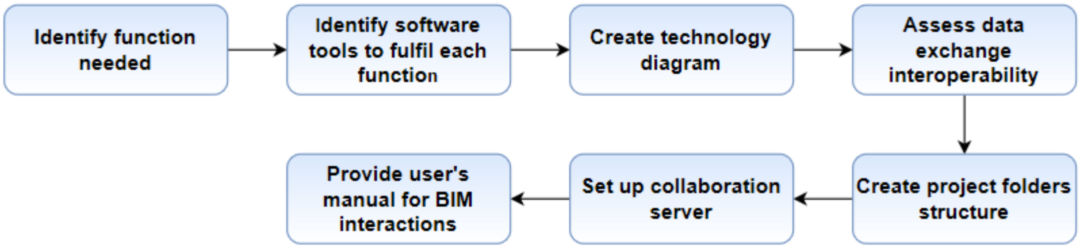


Figure 2: WLC information flow-technology pillar (Dawood and Vukovic 2015)

According to Stark (2011), "Product Lifecycle Management (PLM) is the business activity of managing, in the most effective way, a company's products all the way across their lifecycles; from the very first idea for a product all the way through until it is retired and disposed of". WLC of information flow can be thought of as a part of PLM for the construction industry. Dawood and Vukovic (2015) defined WLC as "the steady and continuous evolution and use of BIM information and knowledge from the design stage, through the construction stage, facility management (FM) stage, and up to decommissioning" achieved through rules or graphical process maps. On the other hand, a Building-Life Cycle (BLC) approach is defined as the integration and consistent evolution of BIM information throughout the project's life cycle (Underwood and Isikdag 2010). BLC consist of the initial planning and design of project, construction phase, operation and maintenance, and dismantling and recycling phase (Farias et al. 2018). As the project evolves from one phase to another, information loses value. For every succeeding stage, the information provided by the previous stage is usually missing, ambiguous, poorly structured, etc. (Dawood and Vukovic 2015). This was the main driver for a WLC approach; to reuse information and prevent its loss. WLC differs from BLC in that the former not only focuses on integration and coordination, but also the knowledge generated along the RIBA (Royal Institute of British Architects) Plan of Work Stages (RIBA 2020). This paper builds up on the research by Dawood and Vukovic (2015), focusing on the technology pillar of WLC, as they interviewed industry leaders in Qatar and compared their views with the UK's industry. In this regard, the findings of Dawood and Vukovic (2015) concluded that BIM technologies do not have major shortcomings. Yet, IFC exchange format caused data loss and geometry distortion during information exchange. BIM data is at the core of the technology pillar, which is why incorporating SWT with BIM is becoming a research attraction in AEC. Within the context of RIBA Plan of Work Stages (figure 3), this research looks into the detailed design stage, relevant to product procurement and asset management. RIBA Plan of Work in its latest update consists of eight stages. According to RIBA Plan of Work, it is essential to understand that highly detailed information will only start being delivered at stage 3 and upwards, as the client's requirements will become clear enough for a detailed design. Thus, it is at stage 3 when the level of input from the engineering team would need to accelerate. This paper is aimed at helping to deliver the objectives of stages 4 to 7. In stage 4 (i.e. technical design), all the design information required to manufacture/construct the project must be complete. Thus, when discussing construction stages, this paper will be referring to the RIBA Plan of Work.

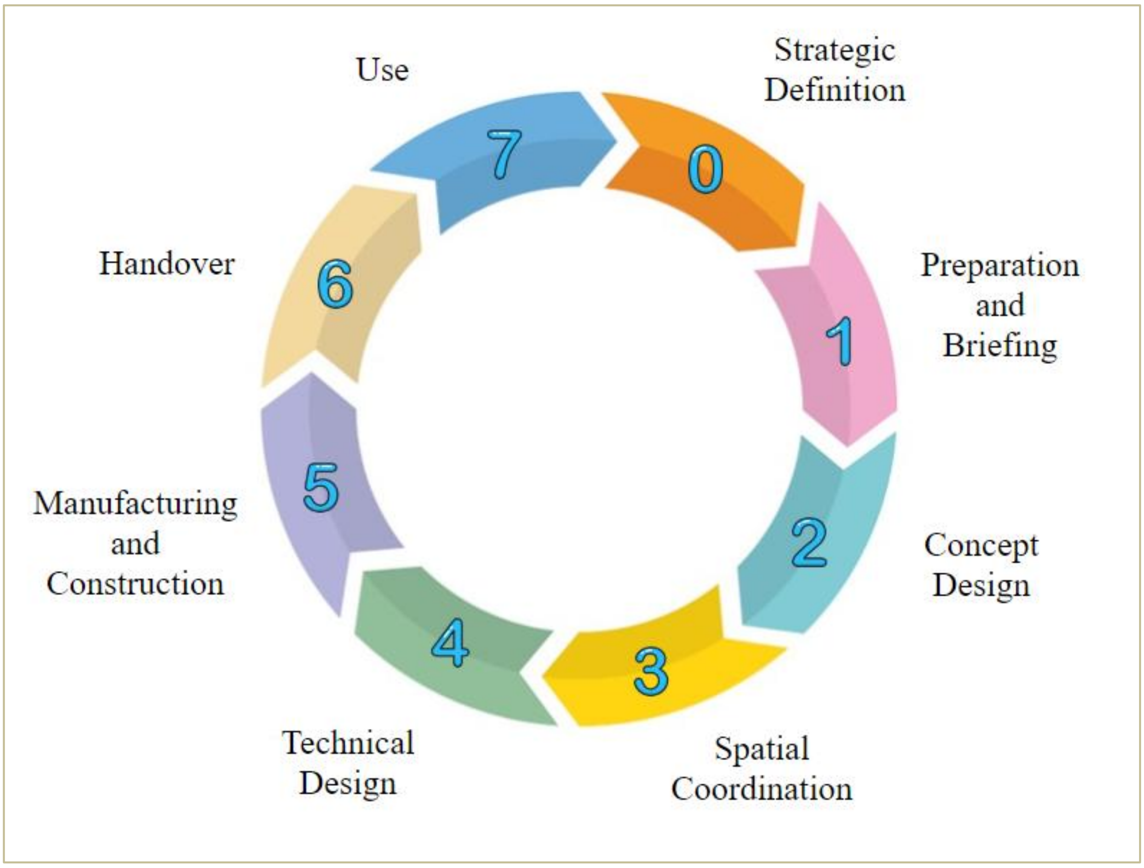


Figure 3: RIBA Plan of Work (RIBA 2020)

## 3 SWT IN AEC

Interoperability, linking across domains, as well as the logical inference and proofs are areas that SWT are expected to enhance within the AEC industry, according to Pauwels et al. (2017). They described interoperability among different domains as loading the same content into multiple applications, and linking across domains as combining different content available in multiple applications. Generally, SWT could allegedly offer improvements to data modelling in AEC, due to linked and continuously updated data. This signifies the importance of creation and maintenance of links between datasets, as Pauwels et al. (2017) argued that this would need human intervention often, resulting in the interoperability issue existing on a finer scale, i.e. at the data level. Nonetheless, SWT tackle data modelling at the finite data level, and thus they harness knowledge representation, which makes SWT of importance across all AEC domains. Abanda et al. (2013); Pauwels et al. (2017) and Zhong et al. (2019) have conducted exhaustive literature reviews on SWT in AEC industry, and the reader is encouraged to explore those resources. However, some of the recent practical applications of SWT in AEC will be presented here.

Rasmussen et al. (2019) created an Ontology for Property Management (OPM), for modelling complex properties in the design environment. They focused on answering competency questions when designing their ontology. Furthermore, they proposed an API to query their ontology and retrieve design data. In general, Rasmussen et al. (2019) concluded that "SWT can be used to cope with the highly interrelated and rapidly changing design decisions when developing a construction project". Kuster et al. (2020) created an ontology for urban district sustainability assessment (UDSA), in which, they incorporated Internet of Things (IoT) technologies. They demonstrated their work via querying the ontology for sensor data. They concluded that the model has proven helpful in achieving a linked data approach for urban district sustainability evaluation. Moreover, Simeone et al. (2019) stated that for built heritage buildings, the informative models are usually semantically poor (data for heritage buildings are usually unstructured, incomplete, or missing). Hence, they proposed a semantic-enrichment framework to enhance BIM models via ontologies. Schneirder et al. (2017) proposed semantically representing the control logic of Building Automated Systems (BAS). They stated that similar concepts can be applied with BIM and BMS (Building Management Systems). The ontological model served as a knowledge base for rule-based verification of control of control logic in BAS. They demonstrated their methodology on controlling an air handling unit (AHU). They assumed that such ontologies can be developed automatically using authoring tools. Yet, Wu et al. (2019) and Barbau et al. (2012) recommended manual development of ontologies to ensure quality. In the context of compliance checking, Fortineau et al. (2019) stated that in a PLM process, rule-related data must be transmitted from one stakeholder to another, which is problematic as these stakeholders would probably use different modelling paradigms. Thus, they investigated rule checking using Semantic Web Rule Language (SWRL) in ontologies to enhance PLM. They focused on integrating existing business rules into a product-centric information system. Kim et al. (2018) proposed a semantic web-based FM database which links BIM data (semantically) to historical work records. Their ontology integrated IFC BIM with FM database. Hence, during the operation and maintenance (O&M) phase, geometry and attributes information are integrated with FM through the Semantic Web. The problem they discussed lies in the data repository; the ability to store, merge, and retrieve heterogenous information. They stated that using object-oriented inferred spatial knowledge can improve work management information (e.g. resource and duration), space management, and energy monitoring. Kim et al. (2018) claimed that to operate BIM in FM using SW, facility managers should be trained in both BIM and SWT. Niknam and Karshenas (2017) created an ontology to represented building information. They suggested having a general, top layer, ontology that would be shared among different AEC domains by extending it to be detailed and specific. In this regard, IFC schema has been developed into an OWL version, namely ifcOWL (Pauwels and Terkaj 2016), which is a current buildingSMART standard (ifcOWL – buildingSMART Technical 2020). However, Zhang et al. (2018) argue that IFC data models are designed for data creation and exchange, but not tailored for querying task analysis. They also stated that IFC does not include the entire spectre of the AEC domain such as building requirements and regulations, product classifications, urban planning, and sensor networks. This paper presents a framework to investigate the benefits of SWT for data integration in infrastructure projects, using a WLC of information flow approach.

## 4 THE CONCEPTUAL FRAMEWORK

In simple terms, the framework is aimed at improving data flow from the suppliers' websites to the relevant asset management software via SWT. Also, SWT are expected to improve data querying and inferencing. The conceptual framework will be discussed in relation to the seven steps of the technology pillar of WLC information flow, figure 2, as well as the RIBA Plan of Work (RIBA 2020), figure 3.

## 4.1 Identify function needed

The paper scratches the surface of the capabilities of SWT. The Previous sections gave a mere introduction to help the reader understand the framework, which is ought to deliver a WLC of information flow for one of the United Kingdom's largest water companies. The current problem lies in the data management techniques; these techniques are further limited by the proprietary asset management software. The company defines its assets according to the Uniclass classification system (NBS 2015) and descriptions of each asset along with its important attributes are stored in Excel sheets as Product Data Templates (PDTs), see figure 4. These PDTs are popular among water companies in the UK (BIM4WATER 2020). The process of acquiring new information, filling in the PDTs, and introducing it to the asset management software is fully manual. According to the company, this manual process is due to the interoperability issue. Therefore, the prime objective of this framework is to achieve automation of this process. The first stage in the process is data acquisition, which is manifested in obtaining good quality product manufacturer data. In this regard, enhancing the process via smarter querying, and consequently, decision making, would allow users to search and choose the most suitable model for the design (Wu et al. 2019). It would be ideal if manufacturers or suppliers published their product data in the RDF format to allow for native querying, which is ought to be regulated by the ISO 23386 (ISO 2020). However, it may take some time into the future for the RDF format to be widely adopted on suppliers' websites. Alternatively, one solution may be to create a dictionary-like ontology consisting of classification clusters of all the related vocabulary for a specific domain. The domain expert (e.g. design engineer) would use this ontology to produce meaningful queries to search product libraries (Gao et al. 2015). Additionally, Geo et al. (2017) used this ontology that they developed to annotate BIM documents and index them. This indexing was done via algorithms to determine semantic relationships. Once an asset is selected from the library, it would then be imported into the BIM model. Though, a problem that usually arises in such systems—in addition to the technological barriers—is determining the attributes that are important for the asset management system or BIM. For example, figure 4 shows some of the attributes of a submersible pump that the water company needs to know for maintenance. Determining the important attributes of an asset is usually an iterative process with no clear methodology, due to the large number of variables involved. This bears the critical issue of clearly defining the requirements in the AEC industry (Alani el al. 2019).

| | | | | |
|---|---|---|---|---|
| Template Version | 2.0 | | | |
| Template Date | 25 May 2018 | | | |
| Suitability for Use | Final version | | | |
| Classification System | Uniclass 2015 | | | |
| Classification Code | Pr_65_53_24_86 | | | |
| Classification Title | Submersible pump unit | | | |
| Creator | [illegible] | | | |
| Template Custodian | [illegible] | | | |
| **Information Category** | **Parameter Name (ISO15926 where applicable)** | **Value** | **Units** | **Notes** |
| **Manufacturer Data** | | | | |
| Specifications | Manufacturer | 1 | Text | |
| Specifications | Manufacturer Website | 2 | URL | |
| Specifications | Product Range | 3 | Text | |
| Specifications | Product Model Number | Test1 | Text | or code |
| Specifications | CE Approval | 4 | Text | number, yes, no |
| Specifications | Approvals | 5 | Text | Eg ATEX, Reg 31(4)(b), WRAS |
| Specifications | Product Literature | 6 | URL | |
| Specifications | Features | 7 | Text | Free text to describe product |
| **Construction Data - Pump** | | | | |
| Specifications | Casing Material | 8 | Text | Eg cast iron, stainless steel |
| Specifications | Outlet Connection Type | 9 | Text | Eg flange or spigot for hose connection |
| Specifications | Impeller Type | 10 | Text | Eg closed, semi-open, open, screw, vortex |
| Specifications | Impeller Material | 11 | Text | Eg cast iron, bronze, stainless steel |
| Specifications | Shaft Material | 12 | Text | Eg Stainless Steel |
| Specifications | Seal Type | 13 | Text | Eg Double mechanical |
| Specifications | Seal Material(s) | 14 | Text | Eg SiC vs. SiC |
| Specifications | Coating | 15 | Text | Eg Fusion bonded epoxy, 250mμ |
| **Construction Data - Motor** | | | | |
| Specifications | Type | 16 | Text | Eg squirrel cage induction or permanent magnet |
| Specifications | Insulation Class | 17 | Text | Eg F, G, H, etc. in accordance with BS EN 60085 |
| Specifications | Insulation Temperature Rise | 18 | Text | |
| Specifications | Method of Cooling | 19 | Text | Eg Air, proprietary coolant, pumped liquid |
| Specifications | Cable Length | 20 | m | |
| Specifications | Cable Type | 21 | Text | Eg BS EN 50525-2-21 (type H07RN-F) (or equivalent) |
| Specifications | Cable Connectors Fitted (Y/N) | 22 | Text | |
| **Dimensional Data** | | | | |
| Specifications | Overall Length | 23 | mm | |
| Specifications | Overall Width | 24 | mm | |
| Specifications | Overall Height | 25 | mm | |
| Specifications | Gross Weight | 26 | kg | Equates to operating weight of unit |
| Specifications | Shipping Weight | 27 | kg | Equates to dry weight of unit plus packaging allowance |
| Specifications | Access Clearance Top | 28 | mm | Access required for maintenance of this item |
| Specifications | Access Clearance Bottom | 29 | mm | Access required for maintenance of this item |
| Specifications | Access Clearance Left | 30 | mm | Access required for maintenance of this item (as viewed from discharge) |
| Specifications | Access Clearance Right | 31 | mm | Access required for maintenance of this item (as viewed from discharge) |
| Specifications | Access Clearance Front | 32 | mm | Access required for maintenance of this item (as viewed from discharge) |
| Specifications | Access Clearance Rear | 33 | mm | Access required for maintenance of this item (as viewed from discharge) |
| Specifications | Outlet Connection Size (NB) | 34 | mm | Eg NB100 - refer to group |
| Specifications | Flange Rating (if applicable) | 35 | Text | Eg PN10 / PN16 |
| Specifications | Impeller Diameter (Fitted) | 36 | mm | |
| Specifications | Impeller Diameter (Maximum) | 37 | mm | |
| Specifications | Manufacturers Drawing Reference No | 38 | Text | Eg Detail drawing reference No from the manufacturer |
| **Performance Data** | | | | |
| Specifications | Lower Limit Rotational Speed | 39 | rpm | Eg Minimum operating speed |
| Specifications | Upper Limit Rotational Speed | 40 | rpm | Eg Maximum operating speed |
| Specifications | Flow Rate | 41 | l/s | Eg At max speed and BEP, based on SG1 - water |

Figure 4: PDT example of submersible water pump

## 4.2 Identify software tools and create technology diagram

Identifying the relevant tools and creating the technology diagram are the second and third steps in a WLC approach, respectively. These steps have been conducted simultaneously, while consulting the literature. Figure 5 shows the proposed semantic framework (technology diagram) to achieve the objectives of this paper. The following steps explain the framework's concept and tools in reference to figure 5.

1. The process starts with the XLS sheets that are used to produce an asset specification ontology (ASO), from their schema. These are the Product Data Templates (PDTs) that the water company uses to describe asset data necessary for maintenance. The PDT for a submersible pump in figure 4 is an example. However, other assets have different criteria to describe them, and consequently, many attributes in these PDTs are not repetitive. There are few translational languages that could automate the process of creating ontologies from XLS sheets, such as TopBraid Composer (TopBraid Composer 2020), and XLWarp (Langegger and Woß 2009). However, as the data in the PDTs are not entirely structured, the process of converting them to OWL should be done manually.
2. The NeOn methodology was used to create the asset specification ontology, by reusing and reengineering non-ontological resources (Suárez-Figueroa et al.

2015). This ontology, which is being developed via Protégé, an open-source ontology editor (Protégé 2020) will consist of classes, attributes, and relations. OWL DL is the language of the new ontology, which includes all the OWL constructs, as opposed to OWL Lite or RDFS-Plus. Some of the OWL DL constructs that were utilised in the asset specification ontology were; owl:oneOf, owl:disjointWith, and cardinality restrictions (Web Ontology Language 2009). Hence, the ontology can be considered as heavyweight (Fürst and Trichet 2006). Figure 6 shows a portion of the developed ontology. As discussed in subsection 1.2, an ontology is a data model that contains three necessary characteristics; formal, explicit, and shared. The ontology in this research is formal and explicit in that it is machine readable and represents real assets (real phenomenon), whilst incorporating Uniclass naming (NBS 2015). Publishing the ontology will be at a later stage in the project.

3. In this step, the asset specification ontology (schema) is deposited in a triple store or graph database, such as RDF4J (Eclipse RDF4J 2020) and GraphDB (GraphDB 2020), respectively. They both store RDF data in a SPRAQL endpoint. Zhang et al. (2018) utilised SWT for improved data querying, as they claimed that current solutions are vender specific. However, even for Semantic Web applications this issue will exist. For example, the chosen data store would affect the process, as most of these databases are proprietary and often encompass different features—such as querying capabilities, once their licence has been purchased. Also, sharing ontologies is another problem that one encounters when working with real life application cases. Due to data protection policies, which is an important research area, full exploitation of Linked Data may be hindered.
4. SPARQL is the query language commonly used to query ontologies. The objective is to use SPARQL to query libraries for product data. As mentioned in subsection 1.2, the more complex the ontology is, the simpler the queries should be. Therefore, as recommended by Allemang and Hendler (2011), this ontology will be designed for querying, which is only reasonable considering the large amount of data in the PDTs. Also, queries are not only to be made on the ontology (via SPARQL Endpoint), but also on the internet for product data according to the parameters specified in the ontology schema. In this regard, Zhong et al. (2018) developed a framework for extending SPARQL queries as defined functions. This framework was to query IFC data, however. Product data, if not published in an RDF format, would need a data converter (see step 6) to RDF format to instantiate the ontology in the graph database.
5. This step in the framework requires identifying the data formats that water assets suppliers use to publish their data.
6. There exist some translational languages to convert data from relational format to RDF such as D2RQ (D2RQ 2020) and YARRRML (YARRRML 2020). As per Akinyemi et al. (2020), when querying across multiple sources over the internet, as in this case, then federated SPARQL queries are to be used. For such on-the-fly querying, Akinyemi et al. (2020) recommended using an Ontology-based Data Access (OBDA) approach. OBDA provides a user-friendly approach to query relational data bases using SPARQL queries (Xiao et al. 2018).

As mentioned earlier, the data providers for this case study rely on the Uniclass naming convention, and so do other large infrastructure companies in the United Kingdom. However, the naming provided by Uniclass may not be suitable for every company as people are not expected to familiar with the entire Uniclass naming convention. In addition to this, classifying assets in different languages introduces even more obscurity in managing these assets. An ontology approach to this matter is ought to form a solution. As explained in subsection 1.2, an ontology assigns an IRI to each resource (classes, properties, and instances) acting as a unique "fingerprint" to these resources. Two resources on the internet with different names but the same IRIs, are ought to be the same. As a matter of fact, the ontology would infer "owl:sameAs" property between them, indicating that they are the same entity. Therefore, it is suggested that Uniclass should introduce IRIs into their classification system to aid solving this ambiguity. In this regard, the Architecture, Engineering, and Construction industry can resemble the biomedical industry. The biomedical industry has resorted to utilising ontologies for unambiguous references to biological concepts, as they have created a wiki space for collecting scientific ontologies, namely the Open Biological and Biomedical Ontologies Foundry—OBO Foundry (Allemang and Hendler 2011). Therefore, perhaps the construction industry should also resort to a wiki space for collecting relevant ontologies, which could be named the Architectural, Engineering, and Construction Ontologies Foundry (AECOF).

This paper is mainly ought to present a framework to support an ongoing case study. The project is currently at the fourth step of the WLC approach, namely assessing data exchange interoperability, figure 2.

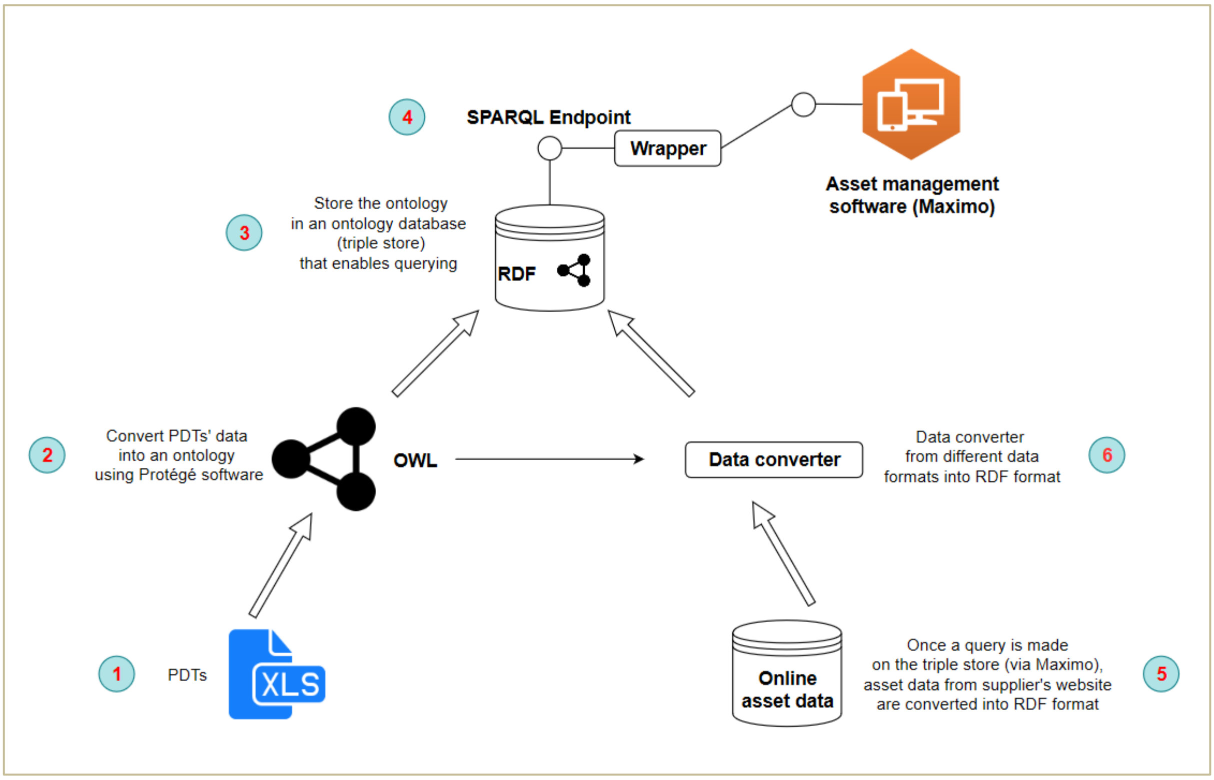


Figure 5: The proposed semantic WLC of information flow framework

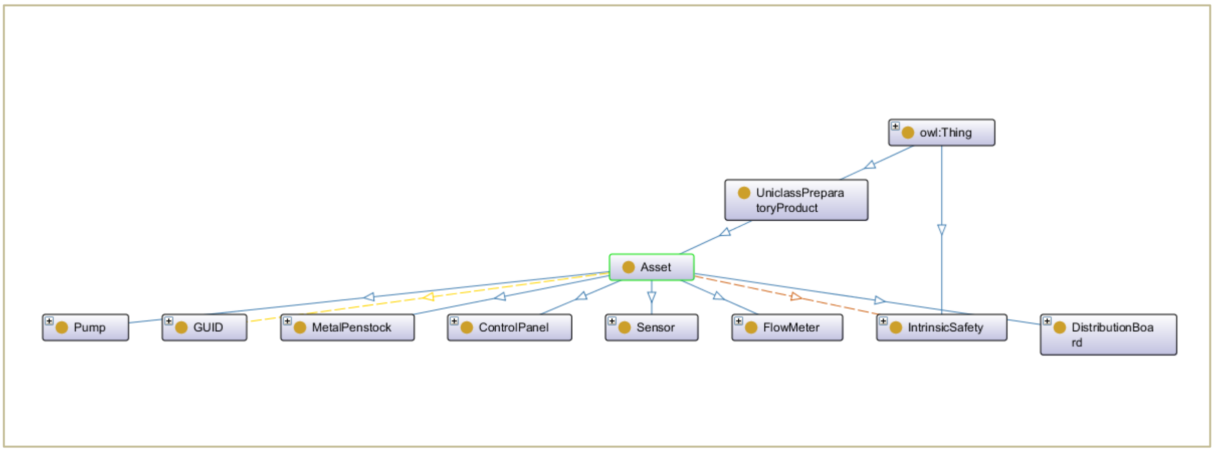


Figure 6: Portion of the water asset specification ontology

## 4.3 RIBA Plan of Work

As mentioned in section 3, the proposed framework is ought to aid the delivery of RIBA Plan of Work Stages 4 to 7 (RIBA 2020), figure 3. Stage 4 deals with the technical design as a responsibility of the design team and subcontractors. This paper proposes creating an asset specification ontology to be utilised at this point. An early asset specification ontology would encourage early facility management involvement, which is a current issue in AEC (Cavka et al. 2017; Alani et al. 2019). Thus, descriptive building system information may be preferred in this regard. Also, the proposed framework would aid the coordination between the design and specialist subcontractors' manufacturing information before the final design data are modelled in BIM. In the Manufacturing and construction stage, the construction team is usually the main actor. However, during this stage, the Semantic Web querying potential can be used on the asset specification ontology to verify design requirements. For example, spatial queries can be carried out via extending SPARQL queries as SPIN functions (Zhang et al. 2018). Similarly, in the Handover stage one of the outcomes is examining the final project pricing to issue the Final Certificate. Users can simply query an asset specification ontology to aid in determining the unit cost of all assets, contributing to the final pricing. The final stage is where most of the tangible benefits of this framework would be found. Most of the building's life cycle costs are during the operational phase (Kassem et al. 2015). It is assumed that the operational phase for utilities companies (infrastructure facilities) such as water companies, is expected to be even more significant in terms of maintenance than the building sector.

## 4.4 Limitations

Expected limitations to this framework include data availability, and data protection and ownership. If some data are not made available by the suppliers, then queries will not return desired results. Discussing the consequences of data protection and ownership is out of the scope of this paper. However, they form major constraints in the field of data sharing and integration.

# 5 Conclusions

Despite current state-of-the-art information exchange technologies such as IFC and ifcOWL, the AEC industry still suffers from inefficiencies of data flow. Particularly, the lack of product manufacturers' involvement in the process when dealing with infrastructure projects other than buildings. In this paper, a framework was proposed based on a WLC information flow approach to validate SWT as a solution to solve an industry-based (water infrastructure) problem, i.e. automating the process of information flow from product manufacturers to the asset management software. The literature seems promising in this regard, as some of the most recent application of SWT in AEC have proven successful. However, using federated SPARQL queries requires establishing mappings between the ontology schema and the data sources which is not a comprehensive solution. ISO 23386 (ISO 2020) is expected to bring benefits in this regard to help achieving Linked Data

One can still argue that research on application of SWT in the AEC industry is not intensively saturated, in comparison to research on BIM for instance. This claim is supported by Zhong et al. (2019) statement that research on SWT in the AEC have only started gaining researchers' interest in the last decade.  This is further manifested in the lack of standards to support a semantic AEC industry. For instance, apart from ISO 15926 (Akinyemi et al., 2020), there were no ISO standards that support/mandate existing ontology deployment in the AEC industry, until the recent publication of ISO 23386 that promotes interconnected data dictionaries.

Data linking capabilities offered by SWT may be constrained due to proprietary licences and data protection policies. Ontologies are about having connected data in a shared environment; creating ontologies may be beneficial for querying, but as long as these ontologies are discrete, the full potential of SWT would be hindered. In general, researchers tend to construct their own ontologies to be tailored for their specific studies, and this paper is no exception. However, there needs to be more efforts on standardising and connecting good ontologies, in a similar manner to the OBO Foundry.

Future work is aimed at carrying out the case study with real data to test the framework, and validate the data using Shape Expressions (ShEx) or Shapes Constraint Language (SHACL) (Labra Gayo et al. 2018).

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# BIM ADOPTION IN THE PRE-CONSTRUCTION PHASE: AN INFRASTRUCTURE PROJECT CASE STUDY

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**Abstract:** BIM adoption represents an uphill task for the construction industry in developing nations. In Brazil, construction companies are looking out for the best strategies to implement BIM into their processes. Currently, the industry relies on traditional methods which fall short of meeting the demand for the interconnection between different levels of information along the building life cycle, especially in highly complex projects. The research goal was to understand the main obstacles with BIM adoption during the pre-construction phase in a complex infrastructure project. The research methodology was exploratory and qualitative carried out through a single case study approach made upon bibliographical research, project analysis and interviews. Based on that, our analysis discussed the results from two different perspectives: BIM adoption in the company's organizational context and BIM adoption in the pre-construction phase. After that, we summarize the main barriers and gaps concerning BIM adoption in the case study. Results has shown the main difficulties faced by the company in their efforts to thoroughly implement BIM. Mainly, the project studied has achieved 3D dimension modeling and a few punctual initiatives of 4D dimension application during the pre-construction and construction phases. In conclusion, this study has observed the importance of the pre-construction phase for the successful information management and project results in terms of constructability, cost saving and time management.

**Keywords:** BIM, BIM adoption, 3D modeling, 4D scheduling, pre-construction phase, construction industry.

## 1 INTRODUCTION

Many decisions during construction are postponed due to the parallelism of design and construction activities faced by highly complex projects such as infrastructure and industrial projects (Francis and Miresco, 2016). BIM has become a common process and technology used in the management of construction projects (Puolitaival and Forsythe, 2016). As an alternative for highly complex projects, construction companies focused on infrastructure and industrial projects are considering BIM implementation in order to minimize problems related to design and construction interface.

However, the construction industry in developing countries such as Brazil is still facing challenges on BIM implementation. The main obstacles are related to the need on the change of work culture and practices, the lack of understanding of the stakeholders 'roles and responsibilities, the lack of knowledge about processes and workflows and the highly investment in training and skills required for BIM (Olawumi, 2018; Mahalingam et al. 2015; Khosrowshahi and Arayici 2012; Singh et al. 2011; Hartmann and Fischer, 2008).

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Considered as an innovative process and efficient technology, BIM manages project information from the design to construction and operation in a collaborative way (Donato et al., 2018). Although in the past decade, there have been significant advances in construction-related collaborative technologies, BIM implementation is a long path and depends on many aspects, such as the adequate methodology, trained personnel, the availability of technology and industry policies (Akintola et al., 2017).

Given the field of study's relevance to the development of construction sector in Brazil, the research goal was to understand the main obstacles with BIM adoption during the pre-construction phase in a complex infrastructure project. This study shows a preliminary result of an ongoing data collection from a case study of a doctorate research. As additional contributions, this paper brings recommendations for the development of BIM adoption in the Brazilian construction industry.

Our paper is structured as follows: First, we introduce the research topic and propose the research goal. Second, we contextualize literature review by discussing BIM adoption in developing countries, BIM adoption in Brazil and 3D/4D BIM modeling applications. Third, we outline methodology characterized by research steps and data collection. Forth, we present case study description by detailing information regarding the company and the project selected. After, we show the results from two different perspectives: BIM adoption in the company's organizational context and BIM adoption in the pre-construction phase. Then, we present the main obstacles concerning BIM adoption in the project selected. Finally, we conclude by presenting research goal achievement, research limitations, future works suggestion and recommendations.

## 2 Literature Review

### 2.1 BIM adoption in developing countries

BIM adoption in the construction industry is growing as technology matures (Turk, 2016). BIM promises an integration of information by combining geometric and non-geometric information in a comprehensive model that accommodate all aspects of construction (Koutamanis (2017). A study developed by Cao et al. (2015), has shown an overview of BIM practice through a decade in China and confirmed that BIM adoption has been clearly extended from the architectural design stage to the construction stage.

Even though BIM has been continually expanding its functionality in the construction industry since its inception in the 1970s, BIM has not been fully exploited even in leading contexts. Mostly, there is a higher level of awareness of BIM in the UK, Canada, Finland and New Zealand then compared to developing countries (Gu and London, 2010; Ghaffarianhoseini et al., 2017). BIM is not just a technology, but also a project management tool and process consisted of all aspects, disciplines, and systems of a facility within a model, with which all stakeholders (owners, architects, engineers, contractors, subcontractors and suppliers) can collaborate more accurately and efficiently than traditional processes (Succar, 2009; Succar, 2015; Azhar et al, 2012).

Despite the rapid development of BIM, the effectiveness in the practice is constrained by the current contractual arrangements and traditional practices. There is a reluctance to change traditional practices and current procedures by the professionals in order to learn BIM. In general, projects are more focused on individual benefits instead of the delivery of integrated project solutions (Love et al, 2014; Migilinskas, 2013). In Brazil and other developing countries, BIM adoption requires a significant change in the way construction businesses operate at almost every level within a building process (Arayici et al., 2011). As stated by Succar et. al. (2013), BIM requires new strands of expertise for all disciplines compared to more traditional projects.

In conclusion, BIM adoption is a continuous and long process which need to be improved step by step passing through all BIM stages. Succar (2009) states BIM stages as Pre BIM: Status of AEC industry before BIM adoption; BIM Stage 1: object-based (modeling); BIM Stage 2: model-based (collaboration); BIM Stage 3: network-based (integration) and Full BIM (the long-term goal of BIM adoption).

## 2.2 BIM adoption in Brazil

In 2017, the Brazilian Government created a strategic committee dedicated to BIM adoption namely CE-BIM to diffuse the usage of BIM in the construction sector though modernization and the digital transformation. Based on a Federal Decree, the Brazilian Government has established the BIM BR Strategy as a national plan of BIM dissemination, systematized by purposes, objectives (indicators and milestones) and actions. Nine main objectives were defined to achieve the expected results (Brasil, 2018):

1. Spread BIM concepts and its benefits
2. Coordinate the structuring of public sector for BIM adoption
3. Create conditions for public and private investments in BIM
4. Encourage BIM training
5. Propose normative and parameters for BIM-based procurement and public bidding
6. Develop technical standards, guides and specific protocols for BIM adoption
7. Develop a platform and BIM national library
8. Encourage the development and the application of new technologies related to BIM
9. Encourage market competition through neutral standards of BIM interoperability.

The CE-BIM has proposed a BIM BR roadmap to be developed in 10 years, from 2018 to 2028 in three main phases. All three phases involve the development of architectural and engineering projects for new constructions, extensions and retrofits:

- Phase 1 (From January 2021): BIM adoption in the design phase. Application of BIM models for clash detections among disciplines such as structuring, electrical, pipeline, HVAC (heating, ventilation and air condition), quantitative take-offs and graphic documentation.
- Phase 2 (From January 2024): BIM adoption in the design and construction phases. Project planning, management and procurement of the construction phase and the design as-built model.
- Phase 3 (From January 2028): BIM adoption in the whole building life cycle phases (design, construction and operation/maintenance). This phase also considers the development of BIM models for facility management.

Therefore, there are many initiatives being developed in Brazil in order to promote BIM adoption in the construction sector. In addition to the Brazilian Government initiative, the Brazilian Association of Technical Standards -ABNT has defined a set of six technical standards related to BIM including modeling object requirements, guidelines for libraries, system classification and information management in construction.

Furthermore, the Brazilian Chamber of the Construction Industry-CBIC has elaborated a guide named by BIM Implementation Collection for Builders and Developers aiming to (Cbic, 2016):

- Develop a clear understanding of BIM applications by orienting its application for construction companies and developers
- Clarify, influence and facilitate a common technological platform between all construction stakeholders.

Allied to the Brazilian government, associations and syndicates from the construction sector have been doing many efforts towards to BIM adoption in the construction sector. Likewise, academia and research labs are developing studies attempting to better incorporate BIM into Brazilian context.

### 2.3 3D/4D BIM modeling applications

BIM is new to many companies and its adoption is consequently challenging. Challenges include unstructured processes that often leads to time and cost overruns (Grytting et al., 2017). Despite the advances in construction management methods and systems over the previous decades, project managers still facing a variety of problems related to the management of partial and heterogeneous data and the manipulation of information (Francis, 2013).

During the pre-construction phase, 3D and 4D modeling techniques can be used to simulate the construction process through a BIM model and detect operation succession errors and space use conflicts (Francis, 2019). As more information becomes available over time and the level of risk decreases, it becomes much easier to make better-informed decisions according to the status of the project or based on the available budget (Francis and Miresco, 2016).

Current scheduling methods do not account for spatiotemporal constraints, which leads to less than optimal scheduling. This failure causes problems which thus affects the project's duration and cost (Francis, Miresco and Le Meur, 2019).

## 3 Methodology

As mentioned before this work aimed to understand the main obstacles related to BIM adoption during the pre-construction phase in a complex infrastructure project. The methodological approach was exploratory and qualitative, through a single case study. As sources of evidence we adopted bibliographical research, project analysis and interviews. The analytic research unit was based on information from the project and participant's answers. Being retrospective, the period of analysis was developed from September 2019 to January 2020. The geographical scope of the study is considered national.

### 3.1 Research Steps

The research was developed in four main steps. First, we concentrated on studying of the topic's theoretical background and on selecting the company. Our main purpose was to investigate a case of BIM adoption in a large construction company in the Brazilian context. Second, after the company and project selection we focused on the project analysis such as project's contract, project scope and schedule, project execution plan and the design deliverables. Third, we interviewed key stakeholders involved in the design and construction phases of the chosen project. Lastly, we focused on data analysis by discussing results obtained from the project studied and the participant's answers.

### 3.2 Data Collection

Data collection was gathered using a semi structured research protocol. The research protocol contains two different semi structured questionnaires which were applied according to the stakeholders' position in the company and project. The first questionnaire aimed to collect data regarding BIM adoption in the company's organizational context. This questionnaire was applied to the stakeholders, who had participated actively in the implementation process.

The second questionnaire focused on the understanding of the main barriers and gaps related to BIM adoption in the pre-construction phase. We interviewed stakeholders involved in the design and construction phases of the project selected. These stakeholders may not had participated in the BIM implementation process in the company.

Most of the data were obtained from the interviews with key project's stakeholders. According to Blumberg et al. (2011) interviews provide rich data collection by allowing an expansion and clarification of questions and answers during the interview process. Clarifications were made by using complementary questions throughout the interviews when necessary. Annotations were made and the interviews were tape recorded and transcribed for content data analysis. Participants were informed the responses remain completely anonymous and confidential. Interviews were applied with five key stakeholders as illustrated in Table 1.

Table 1. Interviewed project's stakeholders

| N. | Company and project's position | Years of experience in the position | Status |
|---|---|---|---|
| 1 | Head of BIM applications/ Bidding | 3 years | Ongoing |
| 2 | Business Developer | 5 + years | Ongoing |
| 3 | BIM specialist | 2 years | Ongoing |
| 4 | Project Engineering Manager | 5 + years | Ongoing |
| 5 | Project Manager | 5 + years | Ongoing |

## 4 CASE STUDY

### 4.1 Company

The company selected for this study is a multinational Brazilian construction company with over 70 years of experience in the infrastructure sector. Since 1948 the company has developed more 885 projects such as industrial, infrastructure, energy, oil, gas and urban mobility all over Brazil and overseas.

With more than 10 thousand employers (office and construction team), the company has five offices spread in Brazil and other six abroad. There are two main headquarters placed in the city of Rio de Janeiro and São Paulo (around 300 professionals) in Brazil. The company's organizational structure is formed by nine corporative units/departments named: finances, planning and risk business, juridical, engineering, management center, supply chain, people management, excellence and innovation, and equipment.

The company is a relevant and well-known construction company in the field which holds several national and international awards and certifications such as ISO 9001, ISO 14001, ISO 19600, OHSAS 18001, AS 8000, SGQ: Sistema de Gestão da Qualidade, SGI: Sistema de Gestão Integrado and PBQP-H: Programa Brasileiro da Qualidade e Produtividade do Habitat (in Portuguese).

In 2018, the head of the company has determined BIM adoption as a fundamental part of the company's strategic planning for the following three years (from 2018 to 2020). Since then, many efforts have been done focused on the spreading of the BIM concept as a work culture initiated by the engineering department to other departments. Once BIM implementation is an ongoing process in the company, the project chosen for this case study is a pilot project of an initial BIM adoption as detailed below.

## 4.2 Project

The project is a Brazilian consortium tasked with developing a thermoelectric power plant for liquified natural gas (LNG) storage. The plant's construction has started on February 2018 and is expected to generate about 1,3 gigawatts scheduled to start delivering energy by 2021. The LNG plant is being built in a 15,700-ha area located in the city of São João da Barra, in Brazil's Rio de Janeiro state. Figure 1 illustrates the project chosen for this study.

Fig. 1. Project selected

The development of the thermoelectric power plant involved six main disciplines, namely: civil, metallic, mechanic, pipeline, electric and instrumentation. The project was developed by a Spanish outsourced engineering company and contractor and is being executed by two other contractors. One of these contractors is the company selected for this study.

The project's scope consists of design, procurement and provision of the equipment's installations, construction , commissioning and start-up of a Combined Cycle Gas Turbine (CCGT) Power Plant with 1238 MW installed capacity and a configuration of 3 x 3 x 1( 3 gas turbines , 3 HRSGs and 1 steam turbine). The gas turbines will have single fuel capability with Natural Gas and the steam exhausting from the steam turbine will be condensed through a seawater cooling tower system.

# 5 RESULTS DISCUSSION

Results are discussed and presented in consonance with the research protocol's structure as cited in the methodology section.

## 5.1 BIM adoption in the company's organizational context

In 2008, the company started the first initiatives related to 3D modeling in industrial projects. Ten years later, in 2018 due to the market demand, BIM adoption was incorporated as a part of the company's strategic plan with the purpose to delivery more value to clients through a digital model and to develop a more integrated process able to manage project information and stakeholders in all project phases.

A team of eight professionals has been created to implement BIM. This team was divided in two different BIM adoption approach. The first team focused on the development of BIM interfaces and the second one on the expansion of BIM applications subdivided into BIM proposal applications and BIM construction applications. As a result, BIM process was delineated to be implemented in three main phases:

- **Phase 1: Structuring (2018):** embodiment of BIM in the company's organizational level. This phase worked on the understanding how BIM could be insert into the actual company project workflow. At the same time, the team focused on the studying of BIM as a concept, management tool, software and process.
- **Phase 2: Training (2019):** investments on professional training, consulting and BIM related courses. This phase aimed to spread BIM adoption into other departments.
- **Phase 3: Implementing (2020):** BIM adoption thorough pilot projects and achieving BIM maturity level gradually by doing trial and error during the design and construction process and by giving feedbacks. At the moment of data collection, the company is concentrated on the activities of phases 2 and 3.

Results have shown the main difficulties experimented by the participants during BIM implementation were lack of trained professionals, lack of digital materials and standards, work culture resistance to the adoption of new technologies, highly investment on training, hardware and software. Additionally, BIM has brought a changing on policies and process practiced by the company.

Since BIM implementation has started in the company, standards and guides are being renewed and incorporated into the design process based on BIM concepts. Also, contracts have been developed in a different way based on the level of development (LOD) by discipline and adapted accordingly to the design typology.

According to the participant's opinion, BIM implementation has impacted more in process when compared to technology and people category. For them, BIM was considered more efficiently in the design phase and flawed in the construction phase. Operation phase was not considered once the company does not work with facility management contracts. Participants responded that they have been receiving positive feedbacks from their clients concerning design quality after BIM adoption. Finally, in a scale from 1 to 5, which one is initial and five is optimized, BIM maturity level was classified between level 2-3.

## 5.2 BIM adoption in the pre-construction phase

During the interview process, our investigation has started firstly questioning if the company adopt any kind of method or solution during the pre-construction phase of the project that helps to mitigate the lack of communication and integration between design-construction phases. After that, we continue by interrogating about BIM adoption during the pre-construction phase itself.

Due to the project's complexity, since the beginning of the pre-construction phase, a multidisciplinary team has been working on mitigating the lack of information between design-construction phases. A team of professionals was composed by approximately 15-25 people from different design disciplines. The number of professionals varies according to the construction work's demands.

Since 2014, the company adopted a web-based platform named by plannerly as a technological tool of design-construction interface. This platform manages all project activities and information by doing a project planning, scoping, scheduling, tracking and viewing during pre-construction and construction phases.

Concerning BIM model applications, the project studied achieved mainly 3D dimension (modeling) and a few punctual initiatives of 4D dimension application (construction scheduling and sequencing) during the pre-construction and construction phases. By considering that BIM still being an ongoing process in the company this scenario could be expected. On the other hand, the participants pointed a list of benefits that BIM adoption has brought to the pre-construction phase such as:

- better understanding of the design scope
- more collaboration among stakeholders
- more interaction with clients
- exchange of information and knowledge management
- design validation (clash detection) among disciplines
- cost estimation and quantity take off.

Finally, participants affirmed that BIM has improved design and construction interface by integrating players from different areas such as engineering, construction, planning and supply chain. Likewise, BIM has brough improvements on site layout, planning and safety, a reduction of claims and risks during the pre-construction and construction phases. As consequence, based on the participant's answers, we believe that BIM has enhanced design and construction interface decreasing project fragmentation by offering a better communication among the design and construction players and a better management of the project information.

## 5.3 Main obstacles concerning BIM adoption

During the interview process we observed a misunderstanding regarding the interaction and communication between the stakeholders. Some of them affirmed that BIM promoted an increasing of interaction between design and construction team. Other ones responded that the physical distance among players was a significant barrier, due to the design team was placed in Spain, the engineering team in São Paulo and the construction site in city of São João da Barra, Rio de Janeiro's state, Brazil.

From our findings we noticed the importance to incorporate BIM in the contract before the beginning of the project. By specifying the level of development (LOD) of each design discipline in the BIM model and how the deliverables would bring more constructability to the construction process in order to help diminishing problems related to the design-construction interface.

Besides the improvements cited before, results have shown the main obstacles and gaps faced by the company during BIM adoption were:

- Difficulty to achieve the necessary level of development of the 3D model able to develop 4D construction scheduling and sequencing (3D+time)
- Difficulty to encourage the players to work together "in the same page"
- Lack of communication among stakeholders
- Lack of knowledge of the design team concerning construction's needs
- Lack of knowledge of the outsourced design's company concerning the usage of BIM
- Lack of interoperability between software
- Lack of collaboration between all design disciplines
- High cost and investment in software and hardware.

## 6 Conclusions and Recommendations

Based on our research goal, we understood the main obstacles with BIM adoption during the pre-construction phase are related to managerial problems than with BIM itself. Therefore, we acknowledge the need of collaborative work environment with design and construction players. We understood the importance to approximate design players with construction job site putting them to work together with the construction team in order to mitigate the problems related to the project fragmentation by improving project's constructability, performance and quality. Furthermore, we recognized the necessity of the construction players started to work in the very beginning of the design phase by bringing their experience of constructability to the design team.

Concerning BIM adoption in the company's organizational context, we know BIM implementation is an ongoing process in the company which has started almost two years ago. Due to the short period of time of BIM adoption we did not expected a different result. As stated by Succar (2009), any company can start from Pre-BIM status and go up direct to Full BIM status. BIM adoption is a continuous and long process which need to be improved step by step passing through all BIM stages. Regarding the BIM level of maturity in the company, we made a comparison between the results and theory. Participants classified the company's level of maturity between 2-3 level which represents in theory from defined (level 2) to managed (level 3) as stated by Succar (2015).

In relation to BIM adoption in the pre-construction phase, we observed a significant concern from the company' viewpoint on providing an accurate information to the construction team from a multidisciplinary design team working on the development of design's feasibility. Therefore, we comprehend the pre-construction phase is a paramount importance for the successful information management and, anyhow, the design professionals and construction players should actively participate on this phase in order to improve project results in terms of constructability, cost saving and time management.

The emergent need for collaborative work involving the design professionals and construction players was stressed along the interviews. This need seems to be even more demanded during the technological transition to BIM processes. The case studied is an example on how construction contracts should change in order to foster collaboration across stakeholders as well as between design and site managers, thereby achieving a higher level of improvement potentially carried on by the new technologies.

The construction industry is a complex and fragmented environment. In developing countries such as Brazil the reality is not different. There is a lack of policies, standards and guides which should be developed from the government sphere in order to brings more quality to the construction industry due to the relevance of this sector for the economic development in the country. The lack of qualified people in the construction site and the lack of knowledge concerning project and process management are another constraint.

Finally, besides the complexity of the project studied and the company's relevance in the construction industry in Brazil, this research has some limitations of methodological approach. First, as a single case study, the findings cannot be generalized. Second, this study was dependent on the participants' self-reported perceptions. Third, new studies should be conducted with others construction companies aiming a comparison between them from a perspective of another project and a different company's organizational structure. An interesting area for future research could be an investigation of BIM adoption in others project's typologies or in the public sector.

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# EXPLORING THE DEVELOPMENT OF A BIM-ENABLED PROCESS FRAMEWORK FOR THE LCA OF RAIL TRACKS

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**Abstract:** A key 21st century infrastructure challenge is lowering cost and carbon over an infrastructure's whole lifecycle. But, accounting for the carbon footprint of a railway system is problematic due to the complexity of railway systems. Within the rail sector, there is still a lack of infrastructure frameworks which can accurately capture actions, interactions and associated processes by role actors during lifecycle analysis. Whilst there is increased focus to facilitate information digitisation in railway systems, there is a scarcity of literature which attempt to systematise and formalise the process of conducting lifecycle analysis (LCA) of railway systems. This paper identifies complexities associated with legacy LCA methodologies in the rail sector. It then proposes a methodology which applies design science techniques to facilitate the creation and re-use of information and data in a systematic way within a structured process workflow. The proposed methodology enables lifecycle information for a rail-track to be produced collaboratively in an integrated format. In addition, the proposed LCA technique allows the creation of LCA process workflows which can be deployed to the web, potentially integrating with other optioneering applications and BIM platforms.

**Keywords:** greenhouse gas emissions, rail tracks, BIM, LCA, process workflow.

## 1 INTRODUCTION

A key twenty-first century infrastructure challenge is lowering cost and carbon over an infrastructure's whole lifecycle; this is particularly crucial for the construction industry which has been reported to produce about 40% of total global waste (Poon 2007) and over 50% of UK greenhouse gas emissions (BSI 2016). In particular, the transport industry has contributed immensely to greenhouse gas emissions such as $CO_2$ (Ortmeyer and Pillay 2001). Greenhouse gases (carbon dioxide, methane, water vapor, nitrous oxide, hydrofluorocarbons, chlorofluorocarbons and ozone) have the capacity to affect earth's energy balance as they absorb and emit its infrared radiation. These gases can have significant impacts on the environment such as climate change especially when intensive environmental human activities (e.g. building and infrastructure construction) promote their release into the atmosphere (Wong and Zhou 2015). This has resulted in numerous studies (Cuenot 2016) focused on quantifying the impact of greenhouse gases especially $CO_2$ equivalents (CO2-eq) during the construction of railway systems. Besides, there is acknowledged efforts by governments (HM Treasury 2013) highlighting the importance of green construction, and of industry (BSI 2016) setting out infrastructure targets. The focus by experts on how railway components affect the environment has also become more pronounced in lifecycle analysis (LCA) methodologies (Chester and Horvath 2009).

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Conventional LCA techniques use specialist LCA software which are also linked with LCA databases. The databases contain thousands of lifecycle inventory (LCI) datasets in different domains, including empirical building and construction energy, and material data. While adopting traditional LCA techniques for manufactured products may be straightforward, the contrast is true for process-based construction processes which often involve diverse project stakeholders and design teams. Meanwhile, fragmentation of processes in the construction industry have been addressed using Building Information Modelling (BIM) which can potentially improve design collaboration and promote design clash avoidance (Akponeware and Adamu 2017). BIM concept which can be traced back to Charles Eastman in the late 70's has no single acceptable definition. The authors of this paper have adopted the definitions provided by Succar et al. (2012) stated thus: "BIM refers to a set of interacting policies, processes and technologies that generate a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle."; and the definition in EN ISO 19650-1:2018: "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions". These definitions underpin how BIM is becoming the de facto standard in efficient information management aligned to organizational policies and processes. Notably, the Digital Built Britain (DBB) strategy launched in 2016 stated that the key to achieving low carbon solutions is the migration to Building Information modelling (BIM) level 3 (open BIM). BIM level 3 promotes the creation and sharing of digital information in a file neutral format within integrated systems. This is a step higher than BIM level 2 which only encourages production of construction information in a digital format whether this be in proprietary software and disparate systems. BIM level 2 has already been mandated on publicly procured projects in the UK. The rail industry is currently moving towards improving environmental sustainability using BIM-enabled solutions (Kaewunruen and Lian 2019).

Elsewhere, the potential of BIM to efficiently manage lifecycle information have been explored in previous studies within the building domain (Najjar et al. 2017; Shin and Cho 2015; Anton and Diaz 2014). Within the rail sector, there is still a lack of infrastructure frameworks which can accurately capture actions, interactions and associated processes by role actors during lifecycle analysis. Further, there are limited studies which attempt to automate LCA workflow processes with data exchanges using an open BIM platform. Some significant problems with the state-of-the-art in the process of quantifying greenhouse gas emissions of a rail system over its life cycle are: the high inconsistencies in different approaches (Ortega et al. 2018; Cuenot 2016), data unavailability (Saxe et al 2016; Esters and Marinov 2014), and process complexity (Anton and Diaz 2014). This problem has led to the development of varying LCA methodologies and approaches which are well documented in literature (Cuenot 2016). This gap needs to be addressed in order to promote both integrated lifecycle assessments but also efficient management of carbon data and information exchanges; a further benefit being that it could potentially feed directly into related researches on Information Delivery Manual (IDM) developments in the rail sector. It was found in the literature that to tackle and control problems with complexities and to formalise interactions in process-based workflows, researchers employed the use of process modelling tools (e.g. see Grefen et al. 2018), and also proposed interaction models (Hoogervorst 2018; Dietz 2006) to specify ontological transactions and actor roles.

Based on this context, the objective of this paper is to propose an integrated platform for structured information and data exchange during the lifecycle analysis of a conventional rail-track by design participants. The realisation of this objective seeks to improve formalisation of LCA methodology and access to consistent and accurate data which can improve the quality of the data produced in LCA studies. The rest of the paper is structured as follows: first, a review of existing approaches to integrate lifecycle analysis (LCA) with BIM in the Architectural, Engineering, Construction and Operations (AECO) domain is presented in section 2. Then, based on the synthesis of the literature, section 3 presented a conceptual framework proposed for conducting the LCA of a rail track. Finally, section 4 presented the main conclusions of the paper.

# 2 LITERATURE REVIEW

## 2.1 Lifecycle assessment applications in the rail industry

LCA methodology which is the environmental branch of the three pillars of sustainability (environmental, social and economic) is the whole-of-life standardised and systematic assessment of the environmental impacts of products and processes (EN ISO 14040: 2006). The LCA methodology follows a 4-step process (EN ISO 14040: 2006; EN ISO 14044: 2006): Step 1-Goal and scope definition; Step 2-Inventory analysis; Step 3-Impact assessment and Step 4-Interpretation phase. LCA studies in the construction industry is executed over the whole-of-life which consist of the following four separate lifecycle phases (BSI 2011): production phase (material extraction, transport and production), construction phase, use phase (including maintenance, refurbishment and replacement) and end-of-life phase (demolition, disposal, and decommissioning). LCA methodology is not new, haven initially been applied in product-based lifecycle analysis. The earliest application can be traced to the USA nearly six decades ago when it was used for the comparative evaluation of different beverage containers (Hauschild et al. 2005). Conducting an environmental analysis can help in the quantification of the impacts of greenhouse gases (or CO2 equivalents - CO2-eq) which are considered to have negative impacts on the environment.

Considering the rail sector, two LCA framings have been recognized when allocating greenhouse gas emissions, depending on whether it is time dependent. The approaches are consequential LCA and attributional LCA methodology (Chester et al., 2013). The former is focused on evaluating the time-dependent system-wide change in emissions, while the later employs average footprint values with the consequent risk of burden-shifting (Jackson and Brander, 2019). There has also been a progressive adoption of the LCA methodology in discrete application types. Thus, some studies have focused on tailpipe (rolling stock) emissions (Dalkic et al. 2017; Andrade and D'Agosto 2016; Pero et al. 2015; Esters and Marinov 2014); while others on non-tailpipe – that is, rail infrastructure emissions (Bressi et al. 2018; Krezo et al. 2018; Ortega et al. 2018); yet a third category on integrated assessments – that is, both tailpipe and non-tailpipe emissions (Saxe et al 2016; Westin and Kågeson 2012). There is evidence that studies on tailpipe emissions are more popular (Rocha et al. 2018; De Martinis and Corman 2018; Meynerts et al. 2017; Chester et al. 2013) owing largely to the ease of their validation via comparison with other modes of rail transport (Esters and Marinov 2014). Contemporary studies by Pritchard and Preston (2018) concluded that studies which ignore the contribution of rail infrastructure might be misleading. They found that studies which discount the emissions of rail infrastructure by only considering use-phase emissions might erroneously promote railway transport as having lower carbon impacts on the environment. This is a motivation for focusing on rail infrastructure (non-tailpipe) emissions in this paper.

Environmental studies on railway systems (rolling stock and railway infrastructure) are relatively new. Some studies were focused on conventional rail types (Chester and Horvath 2009; Facanha and Horvath 2006). Regardless, the processes of quantifying the LCA of rail systems is not straightforward. For example, there is no consensus on the environmental impacts of HSR in the literature. Although, some studies (Dalkic et al. 2017; Jehanno et al. 2011; Åkerman 2011) appeared to suggest that high speed rail is more sustainable in comparison to other modes of rail transport, there is contrary evidence suggesting otherwise (Bueno et al. 2017; Westin and Kågeson 2012). Also, the use of varying lifecycle quantification methodologies discussed earlier exacerbates the current issues.

The problem of the complexity of railway systems has further been identified in the literature. Stripple and Uppenberg (2010) identified seven sub-components of a railway system comprising of tracks, track foundations, tunnels, bridges, stations and terminals, freight and passenger trains, and electric power and control systems. The need for standardisation of approaches to quantify the lifecycle of such a complex system prompted a qualitative and comparative study of existing railway infrastructure LCA approaches (Cuenot 2016). The development of varying techniques and tools to tackle inherent complexities in the railway systems have led to further fragmentation in the Industry. The report by Cuenot (2016) found that the techniques employed in estimating the lifecycle carbon content of a railway is highly fragmented and weak. Ten different methodologies were identified in their study, and it was found that the main reasons for disparities in the literature appear to be: the quality of data used, inconsistencies in the lifecycle phase or boundary conditions, the key assumptions made, and the lack of transparency in adopted methodologies. Whilst these issues are well documented in the literature, the rise of embodied carbon tools offer potential solutions. The use of different eco tools is becoming popular in the infrastructure sector, prompting the need to investigate the relevance of those tools for railway LCA studies and how they also address the problems.

### 2.1.1 Lifecycle assessment tools in the rail industry

A search of the literature by the authors revealed a slow adoption of LCA-based tools specifically suited for the rail industry. Most of the tools found did not specifically address rail LCA studies. The Carbon Planning Tool by the UK's Environmental Agency (2016) specifically addressed low carbon planning solutions within flood and coastal risk management. Athena's EcoCalculator (Athena 2018), developed in the North American region was developed primarily for buildings. The Carbon Critical Knowledgebase Tool (Atkins 2010) is a generic global carbon tool suitable for developing mitigation strategies. The asPECT Tool (Wayman et al. 2012) developed in the UK is intended for Asphalt products in the highways sector. The tool which was found to directly address rail LCA studies was the Rail Safety and Standards Board Tool (RSSB 2015). The Rail Carbon Tool (RSSB) is a web-based eco-tool which was developed to help the rail industry understand and reduce its carbon footprint over the whole-of-life cycle of projects by analysing its energy and material use, together with lifecycle costs (RSSB 2015). The tool also permits carbon scenario modelling making it suitable as an LCA optioneering tool. The optioneering capability is enabled by the tool's ability to analyse various lifecycle impact scenarios and to identify carbon hotspots. The tool however permits limited file exchange and integration with intelligible language-structured systems. For example, at the time of preparing this paper, carbon footprints created in project trees within the RSSB tool could only export to csv and pdf formats. It was also reported by Cuenot (2016) that the tool largely ignored rail infrastructure emissions.

### 2.1.2 Lifecycle assessment data needs

Researchers have attempted to address data quality issues by using LCA data models (Stripple and Uppenberg 2010). However, there is no consensus on how data models should be built up. Both Duan et al. (2015) and Stripple and Uppenberg (2010) found that top-down approaches, which studied the energy and material use, and the emissions and wastes produced were ineffective. These studies promoted bottom-up approaches in scaling up estimates used in LCA assessment since such a technique employed quantity data per local unit making it more flexible and accurate. Access to quality data used for an LCA study by designers could also affect the reliability of the results of the study; but appropriate methodologies needs to make clear what level of data is needed for an LCA study. According to a European Union project of the seventh framework research programme called 'EeBGuide', LCA practitioners have the option of using any of three LCA study types (Wittstock et al. 2012): screening LCA, simplified LCA and Complete LCA. The data quality and quantity increase from lower to higher resolution as the approach moves from a screening LCA study to a complete LCA study. A Screening LCA study is suited for an approximate LCA study (usually in the early design phase while a simplified (or otherwise streamlined) LCA study relies on definitions of the screening LCA study and is suitable for planning purposes since it evaluates additional environmental impact categories. A recent study (Rempelos et al. 2020) adopted the streamlined LCA technique for evaluating the lifecycle impacts of sleeper types in a UK rail network. Finally, a complete LCA study is appropriate for detailed design and covers the full lifecycle of the building or product while adhering to the full ISO 14040/14044 requirements. Formalising railway LCA assessment methodology for a rail component through explicitly stated data exchange transactions could well improve data models as designers are able to specify the required quality and quantity of LCA data and reuse the data models.

## 2.2 Need for formalisation of LCA processes in the rail sector

Although, research in process automations within the rail industry is limited, there is a vast array of researches in other domains on the application of process workflows and the automations of those workflows. It was concluded from the review in the preceding section that formalising railway assessments in railway infrastructure could help designers access high quality data in the early design phase, in addition to re-using the data models which could subsequently lead to more reliable LCA infrastructure studies. In this regard, advanced researches have already been conducted in other domains to model information flow and exchange, the earliest being the use of Integrated Definition for Function Modelling (IDEF0) by Bartley et al. (2016) in a highway project. IDEF0 has a data dictionary and works by modelling the intentions, actions, interactions and activities of a business or project. It is also a computer-generated modelling language with both syntax and semantics. The main draw-back of IDEF0 is its inability to support modern development languages such as the Unified Modelling Language (UML) which therefore limits its interoperability with automated systems. Business process decomposition is underpinned by the principle of *Separation of Concerns* in Software Engineering (Ghezzi et al. 1991). As applied in other domains, a complex process such as the LCA study of a railway infrastructure needs to be treated as a business concern. To allow its consistent decomposition via the principle of *separation of concerns* into integral activities, there is need to extract domain knowledge from experts. Researchers (Dasgupta 1991) in knowledge-related business systems have long accepted that the key challenge in the development of knowledge-based systems lies in extracting domain knowledge from experts and laying them out as separated concerns into a representative model. This becomes more challenging where the domain area is complicated and disparate in nature (Caetano et al. 2012). This leads directly to the main research question addressed by this paper: how can an integrated platform be developed that could aid structured information and data exchange during the lifecycle analysis of a conventional rail-track by design participants?

## 2.3 Mapping infrastructure LCA study with process-based notations

Following the conclusion that LCA infrastructure study needs to be mapped as a process to enable discretisation of the tasks involved in lifecycle assessments, the authors reviewed existing research in process-based modelling and some of the associated standard tools and standards. It was found that while process workflows have been investigated in other domains such as information management, it remained unexplored within the rail sector. Bartley et al. (2016) who used the IDEF0 technique argued that diagrams with standardised syntaxes and notations were better suited for process descriptions. The usability of executable workflows in Compliant Design Procedures (CDP) was explored by Dimyadi (2016). This implemented a client-server architecture where the Microsoft SQL was used as the server and Camunda BPMN process engine functioned as the client. A survey of the literature revealed that although there were many available process modelling tools, Business Process Model and Notation (BPMN) has emerged as a popular tool for modelling organisational processes and workflows. BPMN which is managed by the Object Management Group (OMG) now has a version 2 release called BPMN 2.0. According to Meidan et al. (2017), BPMN is well apt for process modelling, execution and deployment. The ISO 19650-1 (2018) standard recommends two alternative methodologies: process maps and interaction maps for process modelling. Interaction / transaction maps can also be used to represent the role actors and any information or data exchange (called transactions) between them; this makes it also suitable for use as an organisational process modelling tool for complex BIM-based processes.

## 2.4 Embedding LCA with BIM

There is an increased drive in the infrastructure digital industry to discretise and automate tasks using process modelling tools with an extended focus to deploy the processes within integrated platforms. Alreshidi et al. (2016) developed and deployed a combination of processes and data exchange (using the BPMN engine), and business rule sets (using UML language) to a cloud-enabled BIM environment. Meanwhile, Grefen et al. (2018) integrated business goals with both Internet of Things (IoTs) and a reasoning logic called distributed analysis (DA). The goal was to control physical processes which are both complex but also involves multidisciplinary collaboration. The authors found previous studies within the buildings domain which attempted to integrate BIM with LCA and Life cycle cost analysis (LCCA). For example, Anton and Diaz (2014) first suggested the use of 2 approaches to exploit the capability of BIM: (i) exporting BIM quantity take-off in IFC format to a building database which then combines the result with a life cycle inventory (LCI) database to calculate the LCA; (ii) inclusion of environmental properties in BIM object fields based on LCA estimates. Kylili et al. (2016) employed a systematic approach within the water infrastructure domain by selecting a sustainable option between modern Vernetztes Polyethylen water supply system and two systems made from conventional steel and copper. The selection was accomplished by integrating BIM with LCA approach.

Similarly, Najjar et al. (2017) also integrated BIM with the LCA methodology in the design phase of a building construction project to facilitate the assessment and selection of alternative building materials (Type A and Type B). Their work identified three levels of LCA tools already in use; 1st level tools applicable in estimating LCA of construction materials (such as SimaPro, GaBi and Open LCA); 2nd level tools suitable for whole building analysis (such as Energy Plus, Ecotect and Green Building Studio) and 3rd level of tools suitable for LCA during construction and use stage and focused on the 3 pillars of sustainability (such as BREEAM, LEED and Green Globes). Their work involved a partial application of the first technique suggested by Anton and Diaz earlier reported. They integrated a BIM tool (Revit) with Green Building Studio and Tally applications (also in Revit) to select a sustainable building material. There is no indication though that their environmental footprint analysis approach was developed in an interoperable format such as the industry foundation class (IFC) which could limit its use by other non-Revit based authoring systems. Despite the popularity of integrated BIM-based lifecycle studies in the buildings domain, there is a dearth of literature in the rail infrastructure domain focused on developing integrated BIM-based lifecycle solutions.

To conclude the review, it is clear the rail industry needs to adopt practices in information science and software engineering to improve the process of conducting LCA studies. There have evidently been more advanced applications of integrated LCA tools in the building domain when compared to the rail infrastructure domain. The initial steps therefore must be geared towards producing digital information in a structured way to permit re-use of whole lifecycle information produced in infrastructure LCA studies. The information also needs to be machine-readable to enable integration with web and BIM-based systems. Thus, the imperative now needs to focus on discretising the process of a railway infrastructure LCA study to remove complexities and lack of consistencies in the data exchanged among the design team. Such efforts will promote the development of LCA optioneering tools that are suitable for carbon scenario modelling, leading to the selection of low carbon solutions.

# 3 METHODOLOGY

## 3.1 Scope

Given the review of the literature, this paper attempted to relate important concepts, synthesise the literature, and advance the knowledge within the railway infrastructure domain. Considering the complexities and lack of clarity involved in infrastructure LCA studies, this paper situated the main research problem and grounded the study within some main foundational concepts. This is crucial for investigating important network of inter-relationships (Berker 1998). Therefore, the paper adopted a conceptual approach and proposes a methodology for quantifying the LCA of a railway infrastructure using an automated workflow. The overall conceptual framework proposes a client / server architecture; however, the process workflow's server architecture is discussed in this paper.

The carbon footprint (CO2-eq) calculator to be used for the study is the Rail Carbon Tool. This tool uses the Inventory of Carbon and Energy (ICE) database for quantifying carbon emission equivalents. As highlighted in the review, the tool has limited interoperability, however, it will be used as the LCA tool in the initial phase of the study (reported in this paper). The selected rail infrastructure which was used for conceptualisation is a conventional rail track. The choice of railway tracks is only for demonstration but also for ease of access to data in the subsequent phase of the research. Still, the conceptualisation presented here can apply to any railway sub-component.

## 3.2 Conceptual constructs

The conceptual constructs for the study which was adapted from Hevner et al. (2004) is founded on design science research. Design science as a research paradigm seeks to extend existing frontiers in individual and business competencies in order to create a utility (Hevner et al. 2004). Considering the current study, the utility sought to be created is a process-based LCA for a rail-track. According to design science research, it is critical to fulfil the following seven guidelines (Hevner et al. 2004): 1-design as an artifact, 2-define the problem applicability, 3-evaluate the design, 4-provide clear research output, 5-apply research rigor, 6-design effective search process and 7-communicate research. Designing as an artifact requires that the potential solution be able to address a specific business or organisational issue, but this should be done in such a way that the problem can be defined, described and deployed using an Information Technology (IT) solution. An important part of the guideline requires a clear communication of the design-science output to both a technical and non-technical audience. Thus, the solution should be implementable by IT tools and should be easily understood by users (such as management audience) of the information.

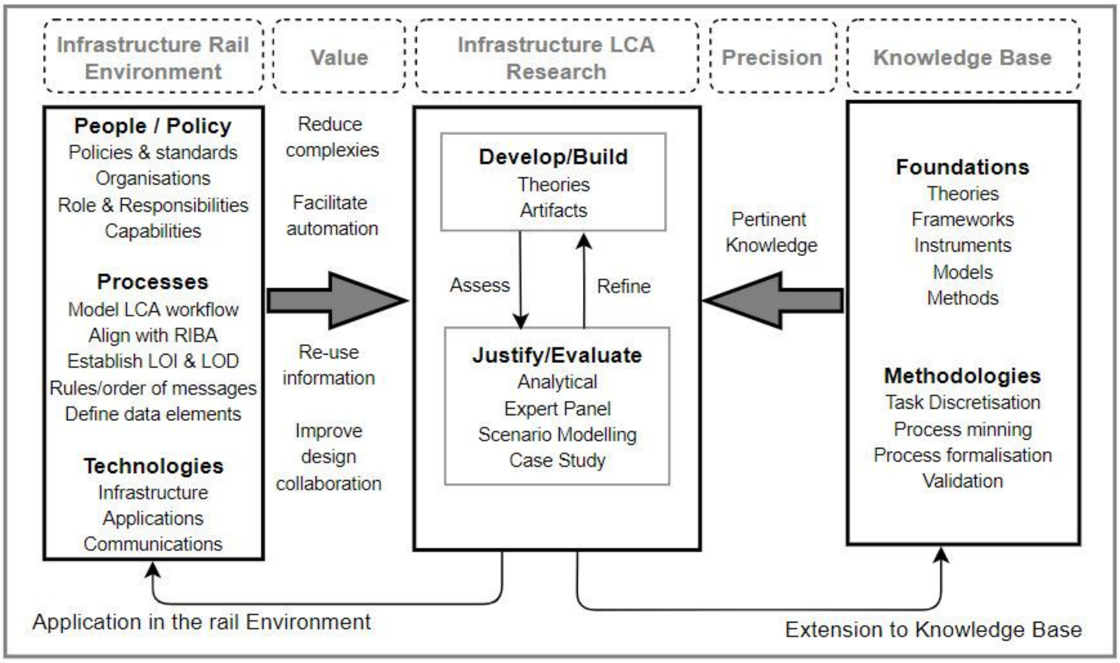


Figure 3.1: Conceptual Framework of the study (based on Hevner et al. 2004)

The conceptual framework for the study is shown in figure 3.1 above and will embed design science guidelines outlined earlier. This is important for conceptualising problems that can be solved using information science strategies. There are three main modules in the conceptual framework (figure 3.1): Environment, Research and Knowledge Base. Dawood and Vukovic (2015) and Succar et al. (2012) identified the core BIM pillars adopted for a whole-of-life construction enterprise and the Environment module has been framed thus to align with these. There is a feedforward between the Environment module and the Research module. In addition, there is a feedback between the Research module and the Knowledge Base module. The expected utility (value) for the organisational enterprise provides the feedforward and is in fact the justification for discretising and automating the process of LCA infrastructure studies. This is iterative as the output from the research can constantly lead to improved efficiencies in processes and technologies, including the identification of the appropriate roles and improvement in organisational culture. An important loop in design science framework as shown in figure 3.1 is the opportunity to improve practice and re-use knowledge through the addition to Knowledge Base. Therefore, it created a potential to represent tacit knowledge in a graphical form, making the process transparent and reproducible. The authors found that this was absent in existing LCA methodologies leading to complexities often acknowledged in the literature.

## 3.3 Illustration of the conceptual framework using a conventional rail track system

This paper's main objective was to propose an integrated platform for information and data exchange during the lifecycle analysis of a conventional rail-track. The conceptual framework set out in section 3.2 will be implemented using the conceptual application described for a typical rail track shown in figure 3.2. Data limitation and complexity was always associated with the LCA of a rail component. Therefore, using organisational and design science theories, it was necessary to delineate a railway lifecycle analysis as a business enterprise or project and to systematise the process. Subsequently, the three design science modules (Hevner et al. 2004) namely environment, research and knowledge base will be applied to the LCA process. Core to this framework is the process mining tasks in the environment module. A designer in the appointing party or lead appointed party (ISO 19650-1: 2018) could coordinate this. The process discovery task could also be used to execute goal and scope definition which is the first phase of the ISO 14040/14044 (2006) framework for LCA analysis.

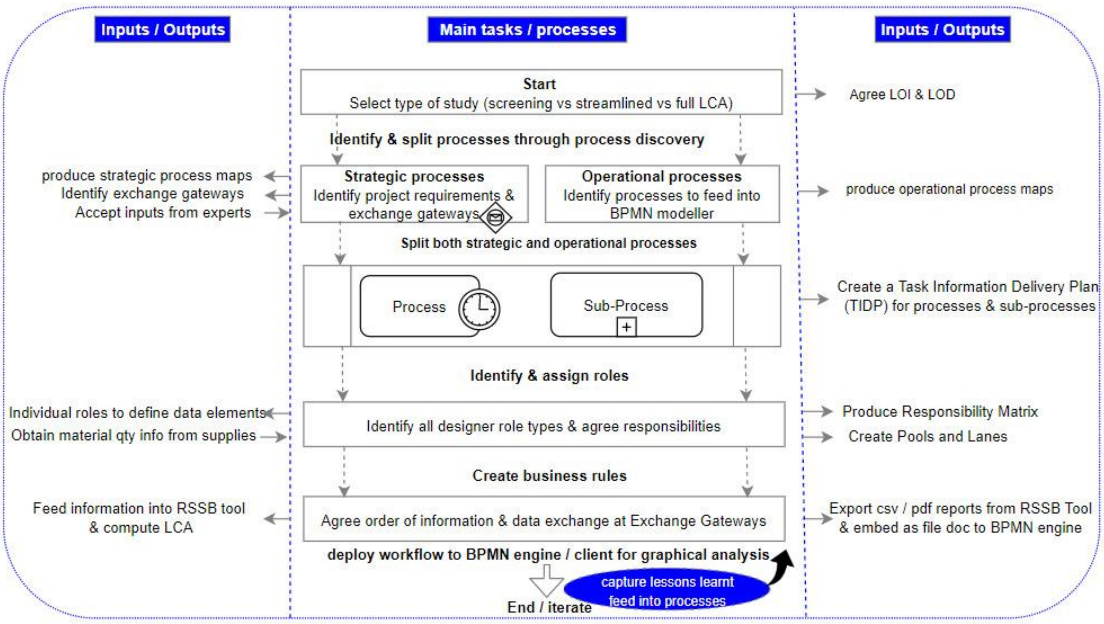


Figure 3.2: Application of the conceptual framework for a rail track

In order to eliminate inconsistencies related to data collection, the framework recommends that the designers select early on the type of study (screening, streamlined or full LCA) as this will determine the system boundaries, level of information (LOI) and level of detail (LOD) to use throughout the LCA study. The designers might want to consider whether global warming potential (CO2-eq) or additional indicators such as particulate matter (PM10 and PM2.5), Nitrogen oxide (NOx) and non-methane hydrocarbons (NMHC) should be evaluated for the environmental analysis. At the operational level, the BPMN tool can be constantly used to add comments, embed files and documents so that all the designers can have access to information as they are sought. The graphical process workflow thus permits collaborators to regularly assess and refine information in order to improve information and data quality. The end of the workflow allows design practitioners involved in the LCA study to capture and provide a feedback or a feedforward of the lessons learnt from the collaborative production of the LCA information. This may be linked with the interpretation phase of conventional LCA studies.

Regarding the selection of tools and technologies for LCA's, design science reasoning requires that this be decided at the strategic level, before passing to operations. The RSSB rail carbon tool has been selected for use in the automated process workflow. Since the Rail Carbon Tool is only able to produce reports in CSV and pdf formats, the initial input of the lifecycle process automation will be fed into the RSSB and used to calculate the LCA of the rail track while the result from the RSSB tool will be embedded as pdf documents as output from the discipline producing it. Since the process workflow is a graphical tool, the initial LCA results can be viewed by the appropriate project participant which may trigger further analysis and communication with other designers.

### 3.4 Architecture of the BPMN workflow for the LCA

The BPMN application which will be used for the LCA task discretisation is ideal for implementing the principle of separation of concerns (Ghezzi et al. 1991) applied in Software Engineering to split deliverables into processes and sub-processes. This can aid formalisation of the deliverable and reduce subjectivity and inconsistencies. Camunda BPMN was adopted for this process in the study. Camunda BPMN is a proprietary Java-based platform and can support process automation. It has both a community (open source) version and an enterprise version. The illustration presented in this paper was executed with the community version. The platform has three main components (figure 3.3): a process engine, a modeller and a web interface support.

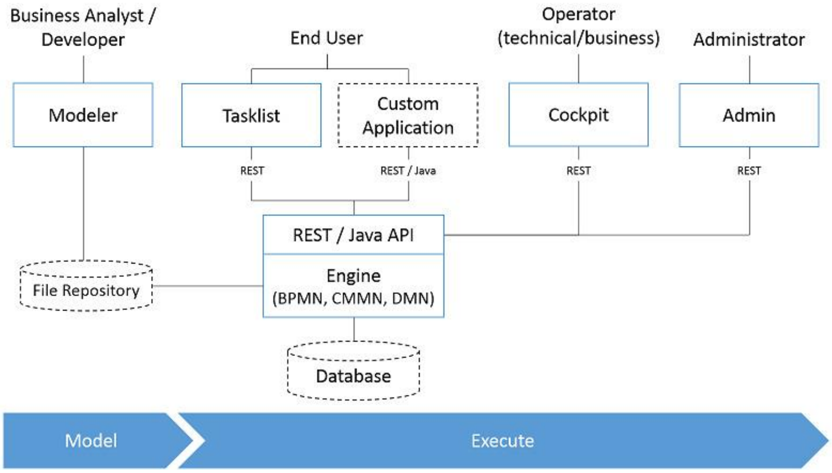


Figure 3.3: Architecture of BPMN process workflow (source: docs.camunda.org/)

Organisation tasks / processes such as those provided in section 3.3 can be modelled in the Camunda Modeller component. However, to automate the processes modelled in Camunda Modeller, a Java Integrated Environment (IDE) called Eclipse was used. It is also an open source software which allows processes to be manipulated using Java delegate implementations. The process applications within the IDE are developed using project templates called Maven. The last component (web interface) creates support for the process workflow to be used on the HTTP protocol via RESTful APIs. Thus, even non-Java developers or designers involved in the lifecycle analysis will be able to create tasks, start processes on the workflow or perform useful analysis.

Once the workflow has been manipulated in code within the IDE, it can be deployed as a Web Application Resource (war) file and opened in Camunda BPMN. Considering guideline 7 (see section 3.2) of the design science theory, the ability to deploy the process workflow to an application server as a war file means that the output of the research (the LCA study) can be communicated in a structured computer language which can be re-used and refined. Camunda has a standalone process engine server which should be run on the computer before the web interface is opened. Apache Tomcat 7.12.0 was installed and used for this purpose. Once all the applications have been installed in the local machine, the LCA of the conventional rail track can be assessed in the usual way using the RSSB tool supplemented with a robust process workflow which is provided by the BPMN process engine.

## 3.5 Potential integration of the BPMN workflow with level 3 BIM

There are several ongoing IFC development projects for railway components pioneered by BuildingSmart. Contemporary researches such as Kwon et al (2018) developed extended IFC capability for railway tracks while previous works by Lee et al (2017) extended existing IFC building information by mapping physical and spatial elements to them. Since the creation of the LCA information and data exchanges could be accomplished in a machine-readable format within the BPMN engine, the output can further be integrated with a server such as BIMServers that can support Industry Foundation Class (IFC) files. A key aspect of ongoing IFC development projects is the expansion to the infrastructure domain in IFC5, which will potentially lead to the use of a file neutral format for railway infrastructure projects.

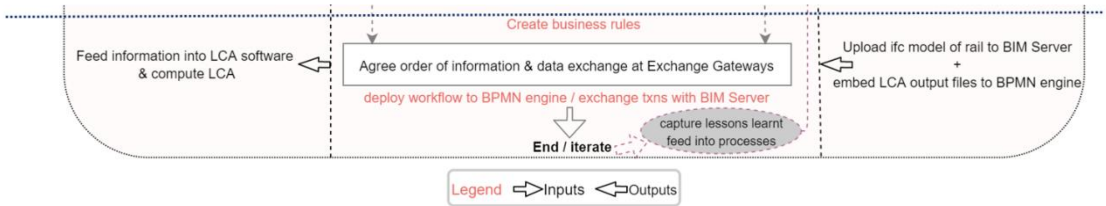


Figure 3.4: Application of the conceptual framework using BIM file-neutral format

This is conceptually illustrated in figure 3.4 under the 'agree order of information and data exchange at exchange gateways' stage. As shown in figure 3.4, an IFC file of a rail track can be embedded as an attachment in the executable BPMN process map. As described in the preceding section, the executable BPMN converts the process map to a *war* file. Transactions can then be initiated between the IFC file located in the cloud BIMServer (level 3 BIM) and the *war* file situated in the client BPMN engine using a Globally Unique Identifier (GUID) for communication. For example, a designer can specify the change of a high carbon footprint element such as a specific sleeper type by specifying the attributes that need to be changed in a form and then sending this to the BIMServer. The server then parses the information and returns an embedded IFC model with the updated information.

## 4 CONCLUSION, LIMITATION AND FURTHER WORK

LCA studies in rail systems have been intensively investigated by researchers. This paper identified complexities associated with legacy LCA methodologies in the rail sector. It then proposed a methodology which applied design science technique to facilitate the creation and re-use of information and data in a systematic way within a structured process workflow. The proposed methodology will enable lifecycle information for the rail track to be produced collaboratively in an integrated format. It also allows the created workflow to be deployed to the web where other participants may choose to refine the workflow with additional optioneering solutions. Moreover, since the creation of the LCA information and data exchanges could be accomplished in a machine-readable format within the BPMN engine, the output can further be integrated with a server such as BIM Servers that can support Industry Foundation Class (IFC) files. The process discovery technique employed within the framework could thus promote more researches on IDM developments within the rail sector. Considering that there is now increasing need to digitise the railway infrastructure sector, the limited interoperability of the RSSB Rail Carbon Tool in open BIM platforms highlights the need for tools which can enable sharing of lifecycle information in an integrated way.

A major source of uncertainty in this study is the assumption that it would be technically feasible to initiate and exchange transactions between the client and the BIMServer. Although there are existing open source platforms in use which can facilitate this, the successful execution will depend on the creation of rail track models in an industry-compliant file format. A future work will therefore focus on validating the conceptual model by creating a file neutral IFC model that is based on a conventional rail track in the UK and initiating transactions with the automated process workflows.

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# PROJECT MANAGEMENT AFTER THE BIM INTRODUCTION: PARADIGM SHIFT OR REITERATION?

**Raissa Freitas[1], Adel Francis[2], Edmond Miresco[3] and Silvio Melhado[4]**

**Abstract:** By the early 2000s, the practical usage of Building Information Modelling (BIM) in the American construction sector was pu181shed by the US General Services Administration (GSA). Since then, BIM usage has been growing all over the world and several new possibilities regarding processes integration are emerging, as well as construction productivity enhancement. As a result, it is generally believed that the practices in project management could have been thoroughly transformed. Therefore, project management academics and professionals that have been working with traditional practices wonder how BIM changes their roles and the pre-existing methods for construction projects. Despite the 20 years of progression in BIM implementation, usage and the unquestionable results, it is still not clear how it is affecting project management and changing the roles in construction projects. Based on a survey with construction professionals and academicians, this paper discusses the effect of BIM over the processes, pre-existing methods and responsibilities, thus contributing to the understanding of what has truly changed and what remains the same in the field of construction project management during the transition from CAD (Computer-aided design) to BIM. Additionally, it contributes to the understanding on how the management professionals deal with the digital transformation regarding construction management, contracts, communication, professional roles, and collaboration.

**Keywords:** Construction, project management, engineering education, building information Modelling, management innovation.

## 1 INTRODUCTION

Eastman et al. (2011) describes how BIM (Building Information Modelling) emerged from intense industrial development and university researches in the 1980s. However, the practical introduction of BIM tools in the construction sector was pushed by the US GSA only in the beginning of the 2000s. The major difference between CAD (Computer-aided design) and BIM systems is that the latter allows the representation of more than just the geometry of an element in a building, integrating information to the model as well. Thus, these are object-based parametric tools where there is an input of a set of relations and rules to stablish geometric features and properties, through the parameters, model families and the hierarchy of parameters.

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Consequently, it seems to be an evolution of design, plan and representation, but would the transition from CAD to BIM be similar to what happened from paper drawings to CAD? When CAD emerged, there was a lot of ideas and insights for its usage, for instance 4D planning integrating schedule-related information (Mckinney et al. 1996; Zhou et al. 2009), virtual reality to enhance visualization of models (Dunston et al. 2003; Whyte et al. 2000) and collaboration design (Rosenman and Wang, 2001). Conversely, nowadays CAD is mainly used for 2D plan drawing and detailing, whereas schedule planning is not combined to it, for example. Therefore, even though BIM has a considerable potential for design and construction integration, planning, cost estimation, sustainability planning and facilities management, all these capabilities idealizations may not be feasible.

Despite that, BIM implementation is increasingly growing worldwide according to Chew and Riley (2013), McGraw Hill Construction (2014), Gledson (2015), Edirisinghe and London (2015), Madeira Filho (2016) and Null (2018). On the other hand, numerous bibliographies also report the difficulties that companies and professionals face when they try to integrate BIM in their work routines, regarding interoperability (Wu and Zhang 2019; Karan and Irizarry, 2015; Arayici et al. 2018; Muller et al. 2017), intellectual property and copyright rights (Porwal and Hewage 2013; Madeira Filho 2017), contractual inadequacies (Porwal and Hewage 2013; Madeira Filho 2017), unclear roles and responsibilities with the advent of BIM (Porwal and Hewage 2013), incorrect usage of BIM tools (Madeira Filho 2017) and imperfect data file with the potential to contain errors, omissions, conflicts, inconsistencies and other inaccuracies (Madeira Filho 2017).

The report from McGraw Hill Construction (2014) shows that BIM return of investment increases directly with a contractor's level of BIM engagement, represented by its BIM experience, skill level and commitment to doing a high percentage of its work in BIM. Therefore, it is clear that the AEC (Architecture, Engineering & Construction) industry is striving to innovate, but at the same time education, procurement techniques, construction laws and contractual arrangements are not following the same path nor the same pace of change. Additionally, these difficulties faced make it hard to have an effective construction project management with BIM, since there are so many challenges to overcome in the project processes, like communication and collaboration, which are not only technical issues but mainly socially and culturally driven.

## 2 LITERATURE REVIEW

The first commercial applications of three-dimensional computer-aided design (3D CAD) were in large companies within the automotive and aerospace industries, as well as in electronics in the 1970s. Moreover, since the 1980s the construction sector adopted it mainly as a two-dimensional tool, the CAD advent gradually changed the design process and professional roles, even if its impact in the construction site would not be considered as significant.

Further, in the 1990s the use of 3D CAD and the introduction of parametric Modelling appeared to be a promise of better connection between construction design and constructability issues. However, only in the 2000's when the BIM technology started to be adopted by the construction sector, the use of 3D representation started to be considered as a significant contribution, mainly because of the possibility to integrate information to the geometry.

According to the Report of the World Economic Forum (2016): “The industry has vast potential, however, for improving productivity and efficiency, thanks to digitalization, innovative technologies and new construction techniques. Consider the rapid emergence of augmented reality, drones, 3D scanning and printing, BIM, autonomous equipment and advanced building materials – all of them have now reached market maturity. By adopting and exploiting these innovations, companies will boost productivity, streamline their project management and procedures, and enhance quality and safety. To capture all this potential will require a committed and concerted effort by the industry across many aspects, from technology, operations and strategy to personnel and regulation.”

The above cited also reports that: “the benefits of BIM are reinforced if companies exploit the new ancillary opportunities it offers – notably, a new way of collaborating and sharing information between stakeholders. Large productivity improvements can be achieved by optimizing existing processes: the broader use of “lean” principles and methods, for instance, could reduce completion times by 30% and cut costs by 15%. Another core lever is early project planning. To improve such planning, companies should promptly draw on the knowledge of all stakeholders, and should explore new contracting models.”

The research of Doan et al. (2019) aimed to identify the elements potentially impacting on BIM adoption. The results indicate that leadership, client and other stakeholders, strategic planning, people, resources, process, measurement, analysis and knowledge management are the most relevant ones. Although many authors highlight most of those elements the approach used for “people” is generally connected to education and training. This paper aims to discuss the impact that BIM caused on the working routine of construction professionals, regarding pre-existing processes, roles, contracts, management, communication, collaboration and the difference between the generations to deal with the same innovation.

Moreover, the construction management process — the system of controls that optimize the design, procurement, and construction process— is the key to the ability of the construction industry to capitalize on technological innovations. According to Gu et al. (2019): “the disconnection between construction management education and the demand for professional talents in China’s construction industry is becoming more and more serious. Construction management education faces new challenges.” Their paper also states the most important dimensions of construction management demand for talents, including the professional practice skills, personal career development ability, and professional knowledge and application.

Concerning the use of digital tools in the construction site, a research published by Morin Pépin and Francis (2019) demonstrate how laser scanning can be a costly, long and even impossible process during construction. Instead, taking pictures as the project advances can be used for inputting information to a previously captured point cloud. The resulting files would then be compared to the 3D BIM model of the building in order to produce a 4D “as-built” simulation. However, this method is limited concerning the inside activities of a building and creating a 3D reconstruction of the building interior is complex. The multidimensional BIM should help project managers and there are several tools that are available to the on-site data acquiring. Nevertheless, the construction culture and its inertial behaviour can difficult their adoption.

# 3 Research Method

This research was based on a literature review and a survey to understand how project managers, construction professionals and academicians are dealing with the advent of BIM and their point of view regarding the impact of it. The method chosen for this research was the survey method, which is used to collect data from a specific sample of a defined population using a questionnaire, according to Visser_et al. (2000). The population selected was construction professionals and academicians from all over the world.

The survey questionnaire is composed with two sections. The first covers questions related to the person's profile, such as profession, age, country, gender, education level, years of experience in the field and company's sector. The second section presents questions regarding the experience with the use of BIM; the perception of the benefits by the individual; opinion related to project team collaboration, communication, construction site management and contracts. The full survey questionnaire is on the Appendix 1.

The possible answers for the questions in the survey questionnaire were multiple answer questions and Likert scale answers. The latter is a technique used to measure the behaviour towards a specific object of study, where the participants are presented with a statement and they must mark their level of agreement regarding it (Ankur et al. 2015).

The answers were collected from January to March 2020. There were 85 participants were anonymous professionals or academicians from 17 different countries. The results section of this paper reports the analysis and the findings on this research.

The questionnaire can be found on the following link: https://docs.google.com/forms/d/e/1FAIpQLSec3DWOmUqtfF1wdp79py3axr3KdaOyj2EPdD0mi-6hcGR35g/viewform

# 4 Results and Discussion

## 4.1 Survey Respondent Profile

The survey was answered by 85 professionals, according to Table 1 the participants were mainly from Brazil (66% - 56 answers) and Canada (11% - 9 answers), but also a considerable amount of professionals from Europe (10% - 8 answers) and Asia (7% - 6 answers). Therefore, the distribution of answers is clearly concentrated on the two countries of this paper's authors and the international characteristic of the research is limited.

Moreover, on Table 2 it is possible to see that the questionnaire was mostly answered by experienced engineers (54% - 46 answers) and architects (34% - 29 answers). As stated on Table 3 there is a high amount of the participants have a Bachelor's (40%) or a Master's Degree (48%), consequently the profile of respondents seems to be higher than professional average. Their ages vary from 26-40 years old (66%) to 41-55 years old (30%) - Table 4, thus the professional generations are not equally represented, consequently the study refers to young professionals mostly.

Table 1: Survey respondent profile - Country.

| From | Percentage | Quantity |
|---|---|---|
| Brazil | 66% | 56 |
| Canada | 11% | 9 |
| Countries from Europe | 10% | 8 |
| Countries from Asia | 7% | 6 |

Table 2: Survey Section 1 - Profession

| Profession | Percentage | Quantity | Comments |
|---|---|---|---|
| Engineer | 54,1% | 46 | This question offers the possibility of typing the professional category. |
| Architect | 34,1% | 29 | |
| Construction Technologist | 3,5% | 3 | |
| Other* | 8,3% | 7 | |

(*) Professors, BIM managers, consultants, interior designers.

Table 3: Survey respondent profile - Education level.

| Profession | Percentage | Quantity |
|---|---|---|
| Master's Degree | 48,2% | 41 |
| Bachelor's degree (University) | 40% | 34 |
| Doctoral degree (PhD) | 5,9% | 5 |
| Postdoctoral degree | 3,5% | 3 |
| Associate's degree (College) | 1,2% | 1 |
| Undergraduate student | 1,2% | 1 |

Table 4: Survey respondent profile - Age.

| Age | Percentage | Quantity |
|---|---|---|
| 26-40 years old | 65,9% | 56 |
| 41-55 years old | 29,4% | 25 |
| Less than 25 years old | 2,4% | 2 |
| 56-70 years old | 2,4% | 2 |

Different construction sectors are concerned in this research, according to the answers on Table 7 there is a concentration of respondents working in the commercial and residential sector, but also a significant percentage of them in the infrastructure and industrial sector, thus helping to generalize the results. Also, the experience profile is concentrated on young professionals, mainly with 6-10 years of experience (37,6% - 32 answers), as it is possible to see on Table 6. In addition, the participants sex is close to equity 52,9% male and 47,1% female, according to Table 7, which is far from the professional reality where women are minority.

Table 5: Survey respondent profile - Activity time in the construction sector.

| Activity time | Percentage | Quantity |
|---|---|---|
| 6-10 years | 37,6% | 32 |
| 21-30 years | 18,8% | 16 |
| 11-15 years | 16,5% | 14 |
| Less than 5 years | 16,5% | 14 |
| 16-20 years | 8,2% | 7 |
| 31-35 years | 2,4% | 2 |

Table 6: Survey respondent profile - Sex.

| Sex | Percentage | Quantity |
|---|---|---|
| Female | 47,1% | 40 |
| Male | 52,9% | 45 |

Table 7: Survey respondent profile - Company's sectors.

| Item | Percentage | Quantity |
|---|---|---|
| Commercial | 47,1% | 40 |
| Residential | 47,1% | 40 |
| Infrastructure | 36,5% | 31 |
| Education/Research | 27,1% | 23 |
| Industrial | 20,0% | 17 |
| Healthcare | 14,1% | 12 |
| Other | 6,4% | |

(*) Non-mutually exclusive answers.

## 4.2 Answers to the questions about the use of BIM

The second part of the survey is composed by questions regarding the use of BIM and its impact over professional activities. Questions from Figures 1 to 6 show the answers' distribution on each topic of the survey questionnaire, which are multiple answer questions. Moreover, Figures 7 to 16 shows the Likert Scale answers, where the opinion of the participants was taken into account. All the graphics below considers a total of 85 answers.

From the pie chart - Figure 1 - it is possible to see that almost half of the participants (47,1%) are beginners' users of BIM, using it only for two years, even though this method came up more than a decade ago. Also, a considerable amount of people has been using BIM for a few more years, from 3 to 5 years, but it is still considered a short time when compared to when this innovation emerged. This seems to suggest that professionals are still adopting BIM in their routine, so there is a long way to go until reach the adequate maturity level.

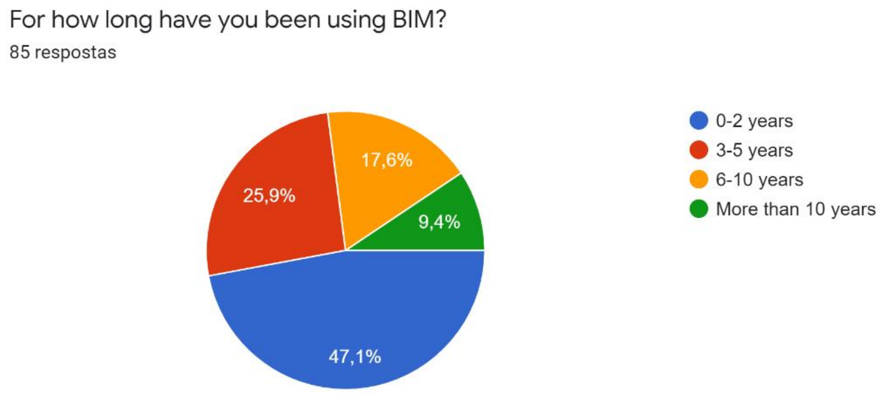


Fig. 1. Answers concerning the time of BIM practice.

Despite this, it is possible to conclude from Figure 2 that most professionals believe that BIM represents an improvement in their processes, since they stated that they partially (44,7%) and fully (48,2%) accomplished their aimed BIM benefits. It is important to set goals when adopting BIM, to track the project's improvements and to ensure when they are achieved.

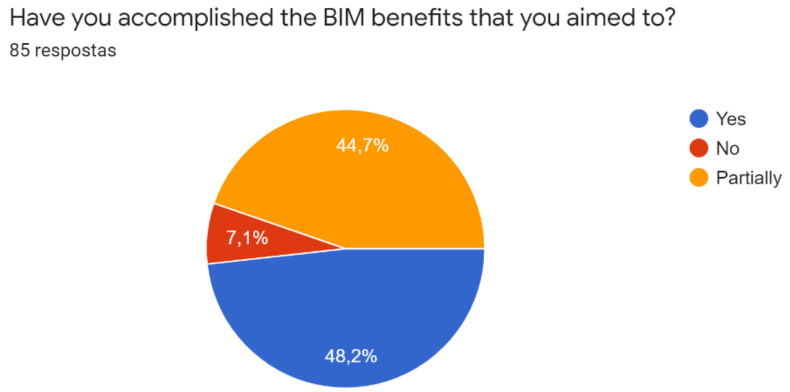


Fig. 2. Answers concerning the accomplishment of benefits through BIM use.

According to Figure 3, when questioned about the BIM impact over project contracts the sample's majority (37,6%) believes that it induced changes on most contracts, 30,6% think that this influence is only on specific projects and 23,5% considers that it always has an impact. A small proportion (8,2%) still believes that BIM doesn't cause an impact on project contracts. However, the World Economic Forum (2016) indicates that BIM proposes "a new way of collaborating and sharing information between stakeholders", thus considering this statement, clearly there must also be a change in the contracts and an impact because of BIM.

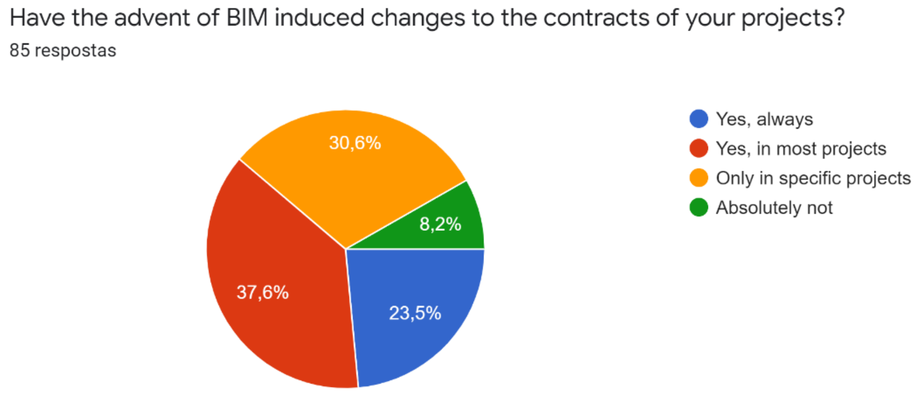


Fig. 3. Answers concerning the BIM impact over project contracts.

Similarly, the survey also covers questions regarding the BIM impact on Team Collaboration, Communication and Construction Project Management on Figures 4, 5 and 6. The BIM experience of these professionals shows that their expectation of improvement on team collaboration and project management was met to most of them (43,5%), according to Figures 4 and 6. On Figure 5, regarding Communication the expectation was met to a considerably amount of respondents (37,6%), but to the majority (49,4%) there was a improvement smaller than they expected on this matter.

Despite the answers on Figure 2 indicate that only 7,1% of professionals believe that they didn't accomplish the benefits through BIM usage, a slighter higher proportion didn't see an improvement on team collaboration (12,9%), communication (10,6%) and project management (20%) with BIM adoption. These are main subjects regarding BIM usage and its benefits. However, these failures to reach better results with BIM can have many reasons related to the adoption process, according to the research of Doan et al. (2019).

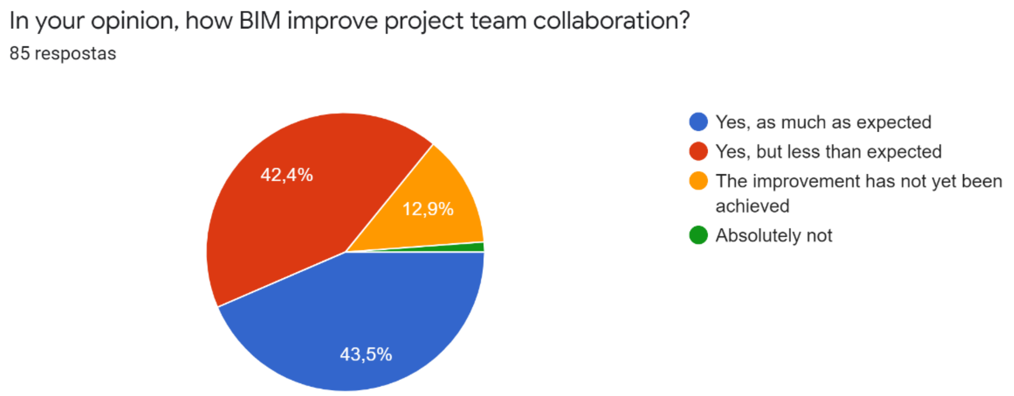


Fig. 4. Answers concerning the BIM impact over project team collaboration.

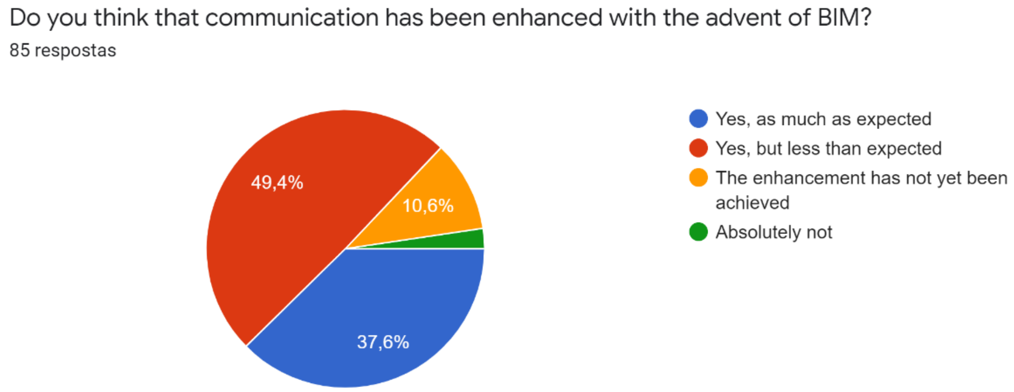


Fig. 5. Answers concerning the BIM impact over communication.

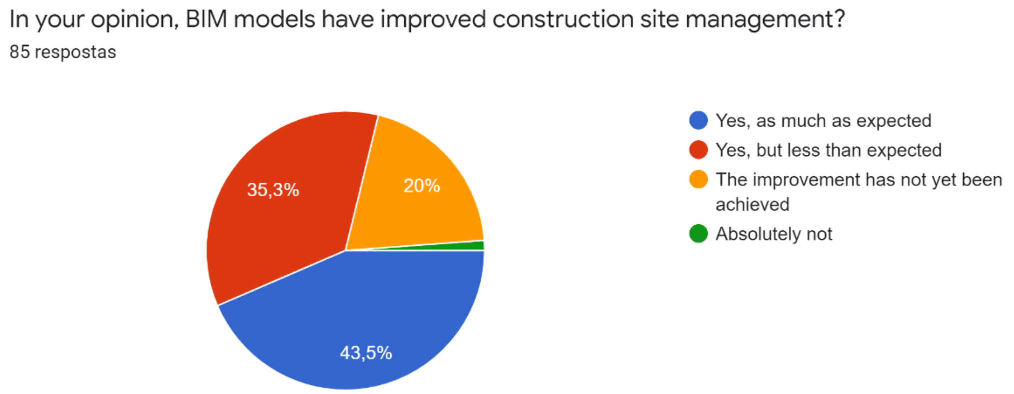


Fig. 6. Answers concerning the BIM impact over construction project management

Figure 7 provides evidence that BIM not only improve internal team collaboration (according to Figure 4), but also enhances collaboration throughout the building lifecycle and among all construction project's stakeholders and disciplines. This is of the utmost importance in a sector where there are so many participants and interactions. In addition, increase on productivity is one of the main goals of the field, which an evaluation of the data from Figure 8 suggests that it is achievable with the use of BIM. Therefore, a considerable amount of professionals that are positive about the outcomes with BIM usage.

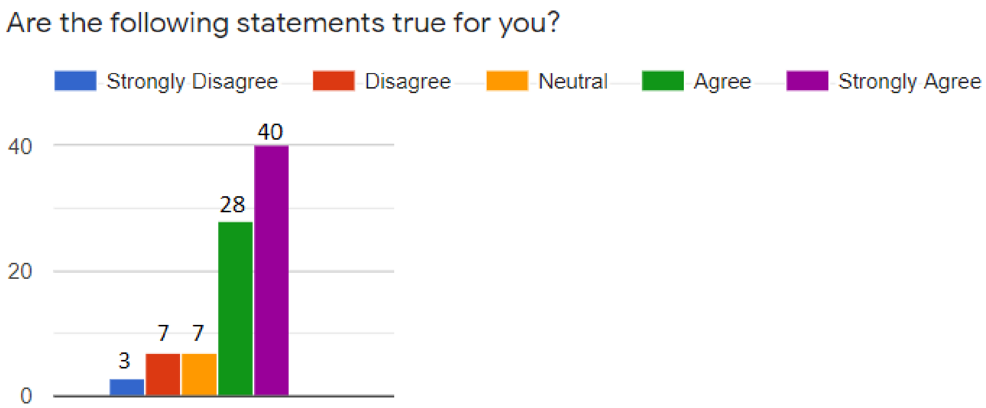


Fig. 7. Opinion question: "BIM facilitates collaboration among all construction project stakeholders and disciplines, from early design to operation and maintenance, so that they can contribute information to and extract information from the central model"

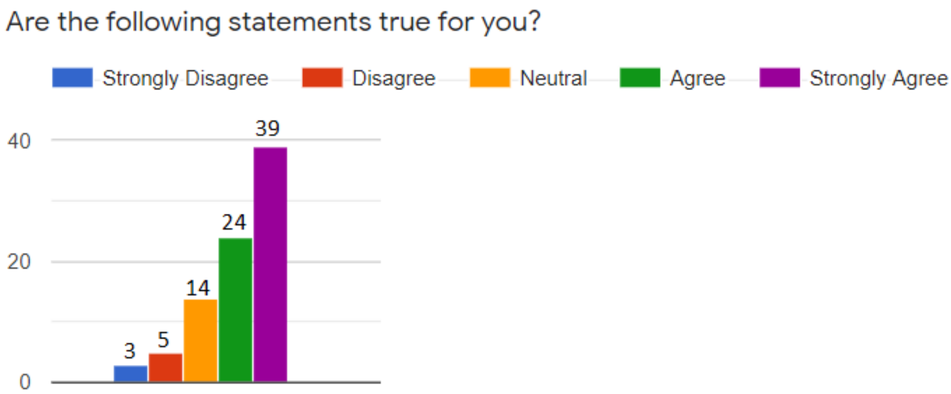


Fig. 8. Opinion question: BIM enhanced productivity in my work

It is common for different generations of professionals to perform daily activities in a distinct way, which differs from the other. One reason for this could be the difference on the education that they received through the years. The advent of BIM and the technology that came with it, demanded a change of behaviour on these daily activities. Even though it is an innovation that came to different generations at the same time, according to Figure 9 most professionals believe that they behave different when performing project management tasks. It is not possible to analyse the motive or the efficiency of this difference. Moreover, the communication between these professionals' generations have also been improved with the advent of BIM according to 56 answers on Figure 10.

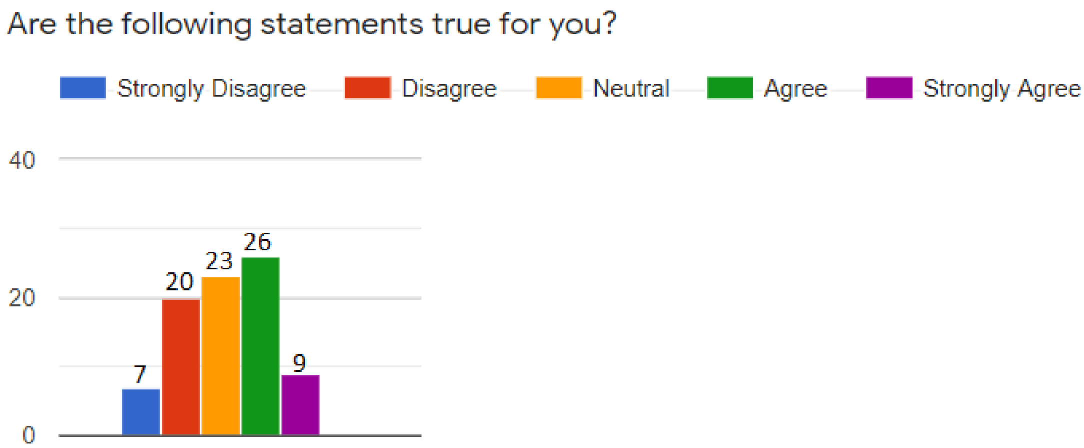


Fig. 9. Opinion question: With the advent of BIM, different generations of professionals perform project management tasks equally

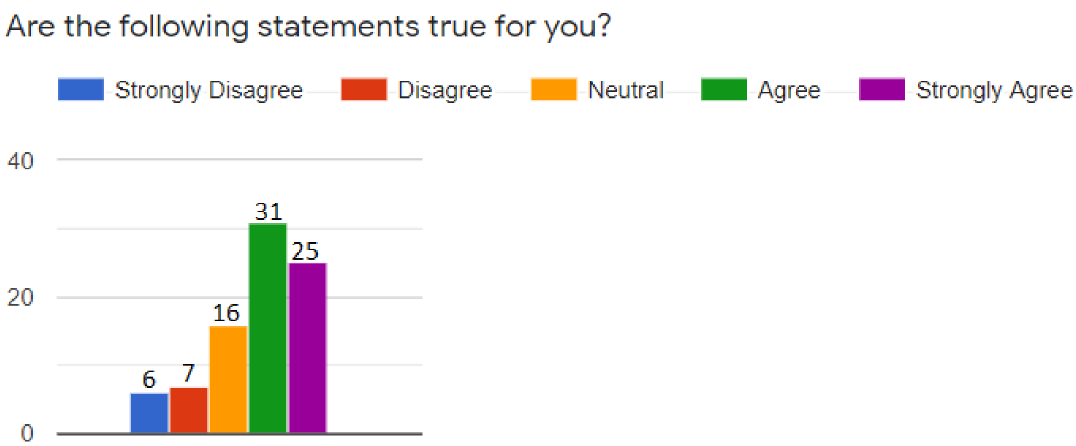


Fig. 10. Opinion question: BIM enhanced communication between different professionals' generations

On the other hand, on Figure 11 it is possible to see that the work routine for 70% of the professionals had a significant impact with the advent of BIM. New guidelines, standards and regulations guide the changes on the way of working with the method, what also have been impacting the professional's daily routine, according to Figure 12. Moreover, from Figure 12 it is possible to conclude that the pre-existing roles are suffering modifications as well, for instance project managers are also becoming BIM managers, because of the new method of working.

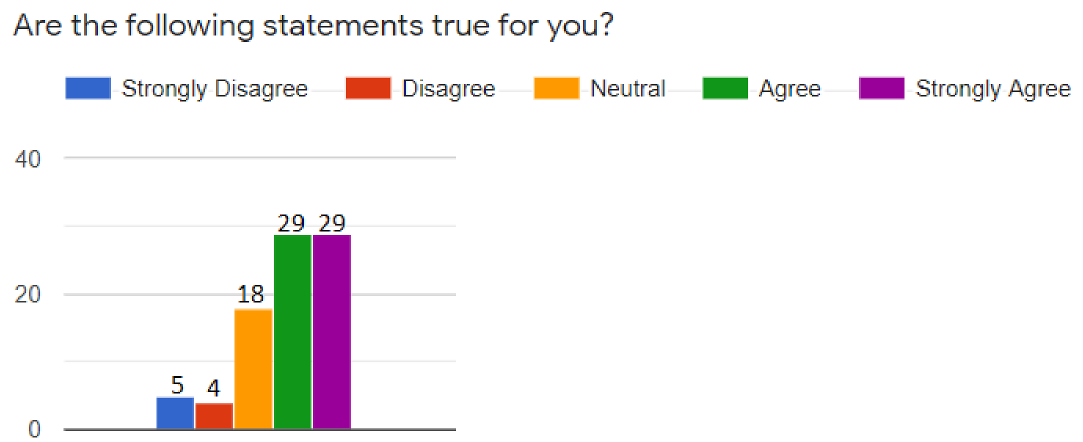


Fig. 11. Opinion question: With the advent of BIM my work routine changed

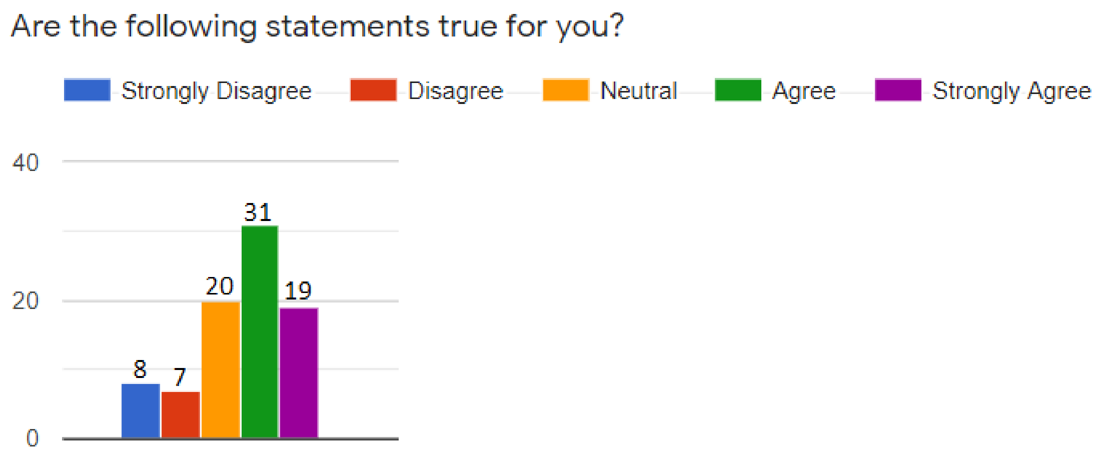


Fig. 12. Opinion question: With the advent of BIM the professional roles changed in my company

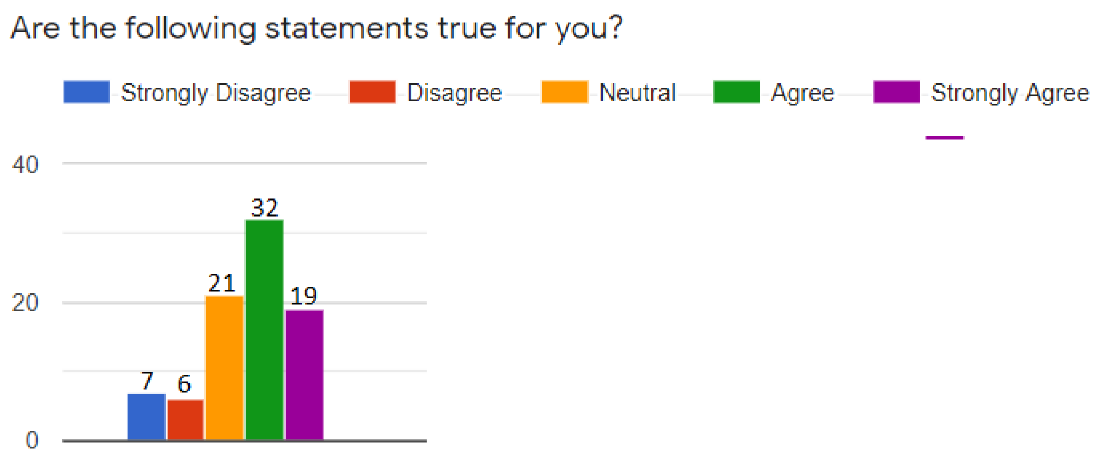


Fig. 13. Opinion question: BIM guidelines, standards and regulations have impacted my work routine

According to a significant proportion of professionals that took part on the survey, BIM is applicable to any size and type of construction project (Figure 16). However, it must be correctly implemented to achieve the aimed benefits. Thus, from Figures 14 and 15 it is possible to see that they also believe that it is crucial to organize the method of working with BIM through the development of a BIP (BIM Implementation Plan), a BEP (BIM Execution Plan) and finally pilot projects.

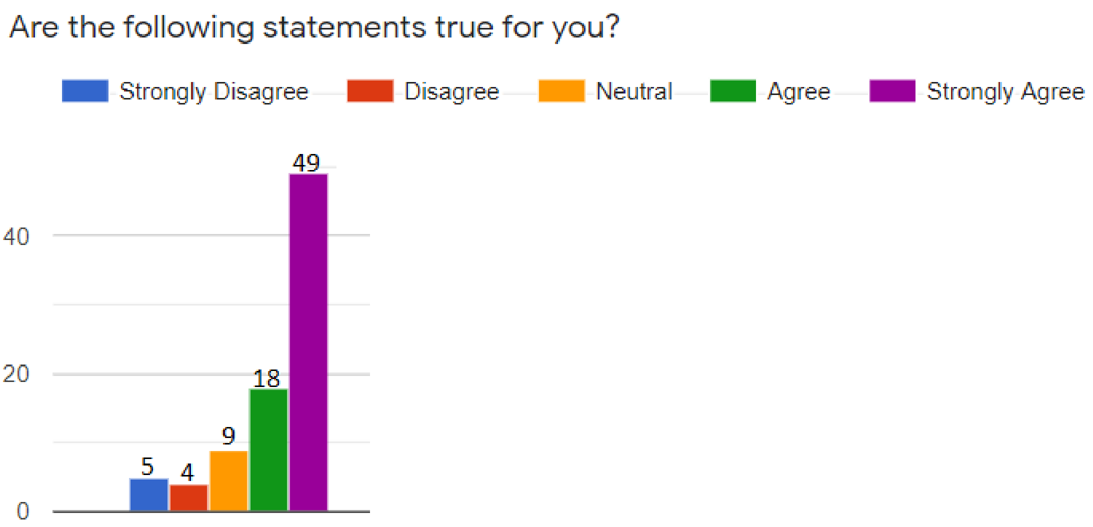


Fig. 14. Opinion question: It is crucial to develop a BIP (BIM Implementation Plan) and a BEP (BIM Execution Plan)

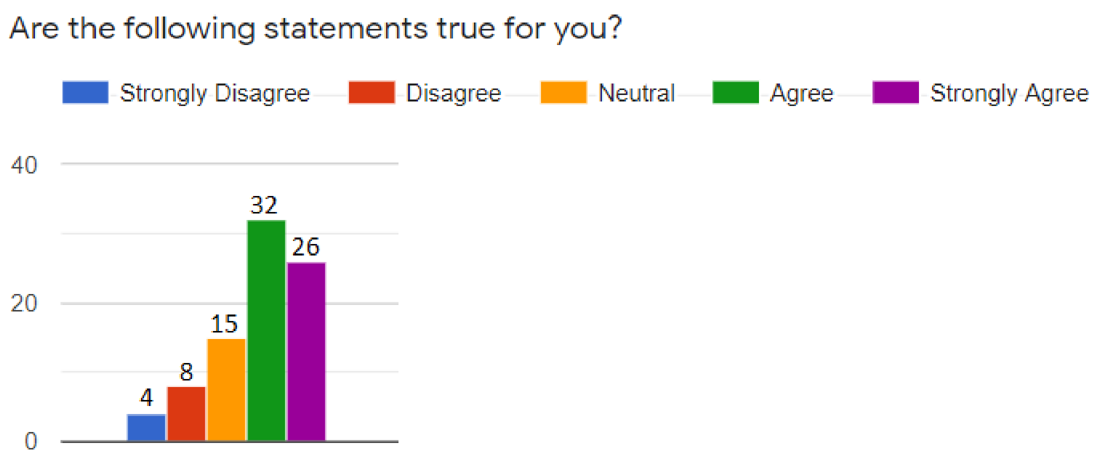


Fig. 15. Opinion question: Pilot projects are the best way to implement BIM in a company

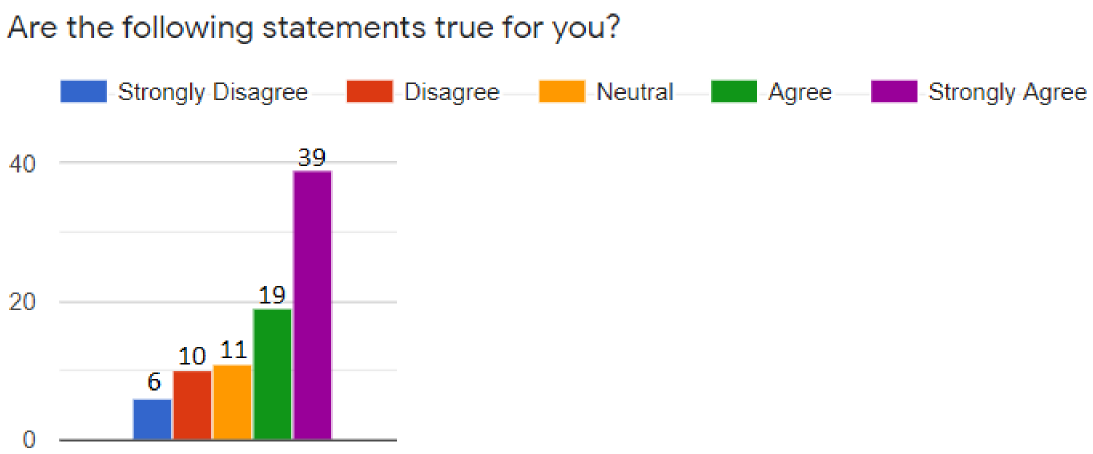


Fig. 16. Opinion question: BIM is applicable to any size and type of construction project.

## 5 Conclusion and Future Research

The transition to the digital era in the construction sector is still in progress. Some structural barriers are hindering the expected evolution in the BIM adoption on the construction section. Legal obstacles, as the obsolescence of contractual models; the evident need to renew roles and responsibilities; the limited educational and cultural basis; the collaboration and communication constraints; and the inertial management practices are some of the factors that originate a low satisfaction of construction professionals with the BIM adoption results.

The usage of this new method is still in the beginning and the innovation must get to a maturity level where it is easy to use it as CAD is nowadays. Despite the limitations of the survey, there are barriers on the way of reaching the highest potential of improvement with BIM. Furthermore, this research will be followed by a set of selected interviews, oriented to a wide range of construction project managers, in order to get a deep understanding on the BIM impact on the professional practices concerning project management.

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## 7 APPENDIX (SURVEY QUESTIONNAIRE)

PROJECT MANAGEMENT AFTER THE BIM INTRODUCTION

1. Which is your profession? (please inform the highest or main degree) *

- Engineer
- Architect
- Construction Technologist
- Building Technician

2. Which is your education level? *

- Undergraduate student
- Associate's degree (College)
- Bachelor's degree (University)
- Master's degree
- Doctoral degree (PhD)
- Postdoctoral degree

3. How old are you? *

- Less than 25 years old
- 26-40 years old
- 41-55 years old
- 56-70 years old
- More than 70 years old

4. How long have you been working in the construction sector? *

- Less than 5 years
- 6-10 years
- 11-15 years
- 16-20 years
- 21-30 years
- 31-35 years
- More than 35 years

5. What is your sex? *

- Female
- Male

6. In which country do you work? *
- Choose your country

7. Company's Sector *
- Infrastructure
- Residential
- Commercial
- Hospitality
- Oil & Gas
- Energy
- Sanitation
- Healthcare
- Industrial
- Education/Research

Your practice in the use of BIM (Building Information Modelling) - Please answer only regarding your personal experience.

8. For how long have you been using BIM? *
- 0-2 years
- 3-5 years
- 6-10 years
- More than 10 years

9. Have you accomplished the BIM benefits that you aimed to? *
- Yes
- No
- Partially

10. Are the following statements true for you? * (Likert Scale Answers)

Strongly Disagree    Disagree    Neutral    Agree    Strongly Agree

- BIM facilitates collaboration among all construction project stakeholders and disciplines, from early design to operation and maintenance, so that they can contribute information to and extract information from the central model
- BIM enhanced productivity in my work

- With the advent of BIM, different generations of professionals perform project management tasks equally
- With the advent of BIM my work routine changed
- With the advent of BIM the professional roles changed in my company
- BIM guidelines, standards and regulations have impacted my work routine
- BIM enhanced communication between different professionals' generations
- It is crucial to develop a BIP (BIM Implementation Plan) and a BEP (BIM Execution Plan)
- Pilot projects are the best way to implement BIM in a company
- BIM is applicable to any size and type of construction project.

11. Have the advent of BIM induced changes to the contracts of your projects? *

- Yes, always
- Yes, in most projects
- Only in specific projects
- Absolutely not

12. In your opinion, how BIM improve project team collaboration? *

- Yes, as much as expected
- Yes, but less than expected
- The improvement has not yet been achieved
- Absolutely not

13. Do you think that communication has been enhanced with the advent of BIM? *

- Yes, as much as expected
- Yes, but less than expected
- The enhancement has not yet been achieved
- Absolutely not

14. In your opinion, BIM models have improved construction site management? *

- Yes, as much as expected
- Yes, but less than expected
- The improvement has not yet been achieved
- Absolutely not

Borges M., Melo R., Giesta J. and Santos D. (2020). "Characterization of the use of BIM in the Brazilian states Rio Grande do Norte e Paraiba" In: *Proc. 37th CIB W78 Information Technology for Construction Conference* (CIB W78), São Paulo, Brazil, pp. 204-217. DOI: http://dx.doi.org/10.46421/2706-6568.37.2020.paper015

# CHARACTERIZATION OF THE USE OF BIM IN THE BRAZILIAN STATES RIO GRANDE DO NORTE AND PARAÍBA

**Maria L. A. E. Borges[1], Reymard S. S. de Melo[2], Josyanne P. Giesta[3], Danilo G. V. Santos[4]**

**Abstract:** Several studies have sought to measure Building Information Modeling utilization on a national scale in many countries, including Brazil. Although it's a diagnostic parameter, the results of BIM macro adoption analysis become inconsistent when compared with the reality of smaller regions, especially in a continental country such as Brazil. Its implementation occurs partially and not homogeneously in Brazilian Architecture, Engineering and Construction companies within the country territory. In a country as vast and marked by inequalities as Brazil, research that analyzes the use of the platform nationally becomes generalist, making its results discrepant when compared with the individual reality of some states. Thus, there is a need to take a regional analysis, trying to avoid generalizations found in previous research. There is little research that does this on a regional scale. This paper aims to evaluate parameters on BIM implementation in Rio Grande do Norte (RN) and Paraíba (PB), two Brazilian northeastern states, a region not covered in previous research. A structured online questionnaire was answered by these states' construction companies to characterize the use of BIM. Results show that RN is a little bit in advantage on BIM usage when compared to PB. The major contribution of this work is the characterization of the BIM use in the states of RN and PB. Understanding local particularities can drive overcoming difficulties that prevent the spread of technology.

**Keywords:** BIM, BIM use, Characterization, Questionnaire.

## 1 INTRODUCTION

Building Information Modeling (BIM) is defined as a set of policies, processes and technologies that lead to the establishment of a methodology for the generation, updating and maintenance, in digital format, of all information relevant to the life cycle of an enterprise (Succar 2009).

Despite many barriers and difficulties, some countries have already started migrating to BIM more than a decade ago and are therefore at a high level of maturity. In a survey of ten countries from North America, South America, Europe, Asia and Oceania, the results show that BIM adoption is considerably accelerating, driven mainly by large contractors and government agencies that want the benefits of faster, safer, more reliable and cost-effective project delivery (Jones and Bernstein 2014).

In the United States, BIM utilization among contractors increased from 28% to 71% between 2007 and 2012. Meanwhile, the same research shows that BIM projects in Brazil

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are still incipient. Compared to the other countries included in the study, BIM users in Brazil are much newer and have a low engagement rate. This index is measured based on BIM usage time, experience level and implementation level (Jones and Bernstein 2014).

Other studies sought to measure the adoption of BIM in Brazilian territory. On a national scale, the research carried out with architects and engineers on the use of BIM in Brazil stands out. The results showed that most of the 588 respondents still did not work with this technology at the time. The research is quite generic, aiming only to identify who uses it and for which purpose (Pini 2013).

Another more recent research has assessed the maturity level of BIM adoption in several countries, including Brazil. A study evaluated and compared the macro diffusion of BIM, which means, on a nation scale, across several countries. Data were obtained by applying an online questionnaire, answered by 99 experts from 21 countries. The results of this research may be considered insufficient to accurately portray the Brazilian reality. While for the UK 16 participants were selected, for a vastly larger country like Brazil only 4 participants were invited. For the evaluation of macro adoption, participants assigned five-level indices to eight requirements. From a total of 20 points, Brazil obtained an average of 5.4. By contrast, the highest-matched BIM nation in the world, the United Kingdom, scored 17.7 points (Kassem et al. 2015).

In Brazil, further mass adoption of BIM is expected in the coming years, as was enacted, in May of 2018, the National Dissemination Strategy of Building Information Modeling. Also called the BIM BR Strategy, its main objective is to spread BIM in the country. In addition, there are government initiatives by some states such as Mato Grosso, Santa Catarina, Paraná, Rio de Janeiro and Rio Grande do Sul. Therefore, it is presumed that the BIM adoption is more developed in some regions of the country than in others, and that the problems faced also vary from one location to another. This is how in a country as vast and marked by inequalities as Brazil, made up of twenty seven states, distributed in five regions, research that analyzes the use of the platform nationally becomes generalist, making its results discrepant when compared with the individual reality of some states. Therefore, there is a need for characterization of each regional BIM uses.

Only a few researches have done this on a regional scale. A study analyzed the adoption of BIM in the Distrito Federal state, through an online questionnaire answered by sixteen of the leading construction companies operating in the residential and commercial real estate market in the state. In this study, questions were asked to ascertain the interviewees' knowledge about the BIM platform, its common uses, results obtained from its application and main difficulties during its implementation or reasons for not doing so. Finally, professionals are questioned about their prospects for using technology over the next five years. Research results indicate that the use of BIM in the Distrito Federal is still small and superficial. The barriers indicated by respondents are complex and mostly involve training and capacity building, a process that happens slowly and has a high cost (Carmona and Carvalho 2017).

Another research also applied an online questionnaire with engineers, architects and other professionals related to the management of construction companies and engineering and architecture offices in the state of Santa Catarina. The objective was to evaluate how the implementation of BIM in the state is being done, after the determination made by the State Government in 2014, requiring the use of BIM for all public works. The questions addressed analyze the knowledge of professionals about the platform and how they are using it. More than 90 companies from Santa Catarina participated in the research and allowed to better understand how the process of implementation of BIM in the state is. It was noted that most companies were preparing to meet the required standards (Steiner 2016).

Understanding local particularities can drive overcoming difficulties that prevent the spread of technology. The best path for implementation in one location may not be the other because it faces different obstacles. Precisely because it understands that these differences exist, even with the BIM BR Strategy launched, the state of Rio de Janeiro instituted in October 2018 the BIM RJ Strategy, in accordance with Decree No. 9,377. The tendency is for this to happen to other states, as the Brazilian Chamber of BIM (CBIM, by its acronym in Portuguese) itself has split into the Brazilian states. Therefore, the characterization of the regional adoption of BIM becomes crucial.

Given this, by characterizing the use of BIM in the states of Rio Grande do Norte and Paraíba, this paper aims to bring parameters of the adoption of BIM in two neighboring states of the Northeast, not yet contemplated in previous research. In addition to filling this theoretical gap, this study differs from the previous ones by addressing in its questionnaire the temporal particularity of economic recession that Brazil has experienced in recent years.

## 2 INCENTIVES FOR BIM ADOPTION IN BRAZIL

Gradually BIM is no longer a trend and becomes a reality for the construction indus-try. Its adoption is growing year by year and the expectation is that most companies will eventually adopt the technology, such as did the transition from drawing boards to Computer-Aided Design (CAD) in the early 1990's and 2000's. Enterprises are likely to be gradually disqualified in the labor market if such adoption occurs late or, in some cases, it doesn't happen (Eastman et al. 2008).

Greater gains are identified for the adoption of BIM when it is combined with actions by government agencies in the definition of mandates indicating the guidelines and standardization required in the use of the methodology (Smith 2014). This movement is evidenced by the growing intensity of discussions around BIM and the accelerated availability of Notable BIM Publications (NBP's). NBP's are publicly available indus-try documents incorporating guidelines, protocols, and requirements focused on BIM products and workflows. These publications are the product of various agencies, industry associations, communities of practice, and research institutions designed to facilitate BIM adoption and achieve BIM's added value potential.

Therefore, as a way of encouraging its implementation, several efforts have been made by companies and governments, from the elaboration of guides to the requirements of rules and exclusive bidding for BIM projects. Countries such as the United States, the United Kingdom, Finland, Singapore, Norway, and Hong Kong are pio-neers in guideline publications that present strategies and approaches from govern-ment initiatives. Such standardizations help ensure the most appropriate targeting of efforts for lasting investments in BIM deployments in the enterprise market (Farias et al. 2016).

In Brazil, there are two major NBP's, the "AsBEA Guide: Best Practices in BIM" (2015) created by the Brazilian Association of Architecture Offices and the other one is the "BIM implementation in Builders and Developers" (2016) developed by the Brazilian Chamber for the Construction Industry (CBIC, by its acronym in Portu-guese).

In addition, in May 2018, the Brazilian government passed Decree No. 9,377. Through this, the national BIM dissemination strategy was instituted, something that had been foreseen since the creation of CE-BIM in June 2017. Isolated initiatives by

Brazilian state governments are also observed. Through the State Secretariat of Infrastructure and Logistics (Sinfra), Mato Grosso (MT) was the first Brazilian state to launch a bidding for 3D projects for highways requiring the use of BIM. In October 2017, Sinfra presented the bid notice for companies to execute 3,500 km of roads projects using the BIM platform.

The MT's initiative represented great advances, but Santa Catarina (SC) is the first Brazilian state to require the use of BIM for all public projects since 2018. Therefore, the "Caderno BIM" was published, a NBP that contains the procedures for project development following this methodology in SC.

Still in 2014, in the state of SC, the Technical Working Group for the implementation of BIM was also created and a technical cooperation agreement was signed with the Paraná Department of Infrastructure and Logistics to introduce BIM in both states. At the end of 2016, the state of Rio Grande do Sul also formalized an agreement with the SC to exchange experiences on technology (Steiner 2016).

Finally, in October 2018, the Government of Rio de Janeiro instituted the Building Information Modeling Dissemination Strategy, or BIM RJ Strategy, whose purpose is to provide a suitable environment for investment in BIM and to promote its diffusion in the state, in parallel to Decree No. 9377.

## 3 RESEARCH METHOD

Structured questionnaires were applied using the Google Docs tool from June to July 2018 in construction companies based in the Rio Grande do Norte and Paraíba, aiming to characterize the use of BIM in these Brazilian states. Figure 1 shows the flow chart of the questionnaire.

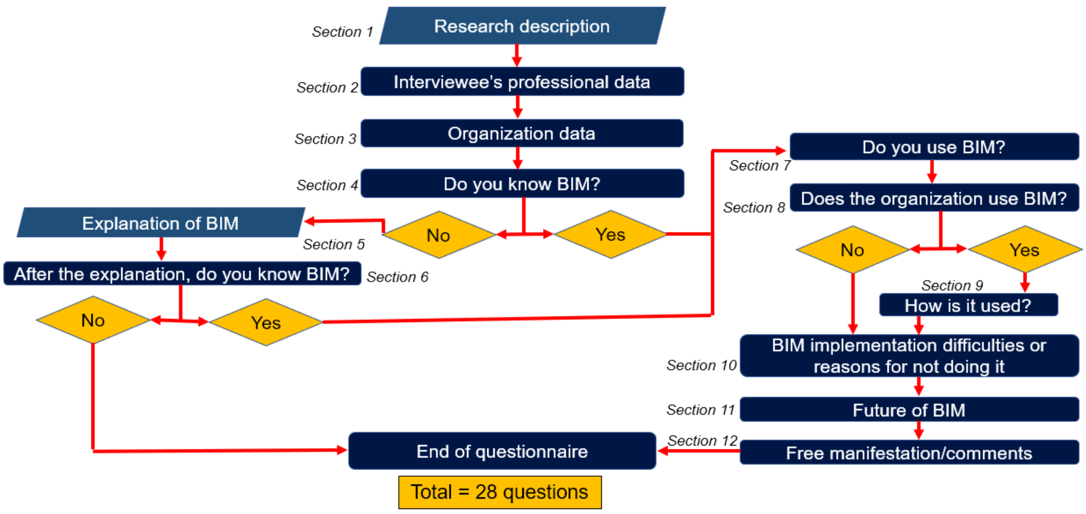


Figure 1: Questionnaire flow chart

The questionnaire is adapted from Carmona and Carvalho (2017), who investigated the adoption of BIM by sixteen of the main construction companies operating in the residential and commercial real estate market of the Distrito Federal state and the major difficulties faced during its implementation. It analyzes the interviewees' and companies profiles, the degree of the BIM uses, as well as the purpose of its application. Also, the major difficulties in its implementation or the reasons for not using it are questioned. In addition to modifying some questions from the original questionnaire, questions related to the recent period of economic recession in Brazil were added to this current study.

In order to analyze the degree of adoption and to qualify the use of BIM in the states of Rio Grande do Norte and Paraíba, the structured questionnaire link was sent to companies operating in the local construction sector associated to the Construction Industry Syndicate (Sinduscon, by its acronym in Portuguese) of both states. Due to its ease of creation, survey responses and gratuity, the Google Forms platform was used to complete the questionnaire, which was sent in emails with a brief explanation about the survey.

Aiming to increase the number of answers and obtain impartial information, the questionnaires were designed to ensure that the respondent could not be identified while maintaining their privacy.

To ensure greater visibility of the survey by respondents and acquire a higher response rate, the Sinduscon of both states agreed to forward the survey link by their own institutional emails. While in Paraíba a high percentage of responses was acquired, in Rio Grande do Norte only a few companies collaborated with the survey.

The initial intention was for the questionnaires to be available online for two weeks, however, because the number of responses in the RN state was not satisfactory, the period was extended for another two weeks, accounting for one month. Due to this adversity, it was necessary to resubmit the questionnaire directly to company employees and request that they respond. As a result, the stipulated period for keeping the questionnaire online went from two weeks to one month between June and July 2018. This attempt to obtain more data for the analysis resulted in almost four times the responses initially acquired.

# 4 RESULTS AND DISCUSSION

Table 1 shows the number of companies affiliated with the Syndicates, the number of answered questionnaires and the percentage of that number represents over the total.

Table 1. – Percentual of answered questionnaires

| Syndicate State | Affiliated Companies | Answered Questionnaires | Answering Rate |
|---|---|---|---|
| RN | 101 | 32 | 31,68% |
| PB | 168 | 38 | 22,62% |

To analyze the answers, the questions were classified into the following seven points: professional profile, organization profile, knowledge of the term BIM (before and after explanation of the term), use of BIM and usage characterization, implementation difficulties and future projects for use of BIM.

## 4.1 Professional profiles

This parameter sought to analyze the position held by the professionals in the company, their education and experience in the field of construction. The answer to the position held was free and the classification adopted was between managerial and non-managerial occupations, according to Figure 2.

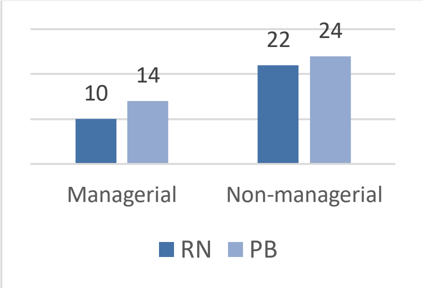


Figure 2: Positions held in the organization

According to Figures 3 and 4, most of the interviewees has a graduation in Civil Engineering and they are in the job market between 5 and 10 years (relatively short period) and occupy non-managerial jobs in their companies.

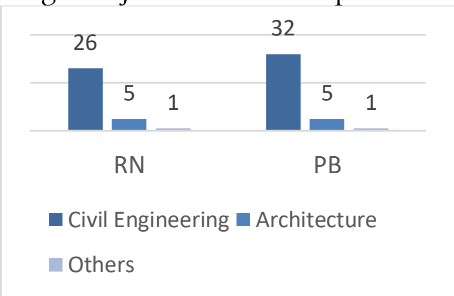


Figure 1: Graduation area

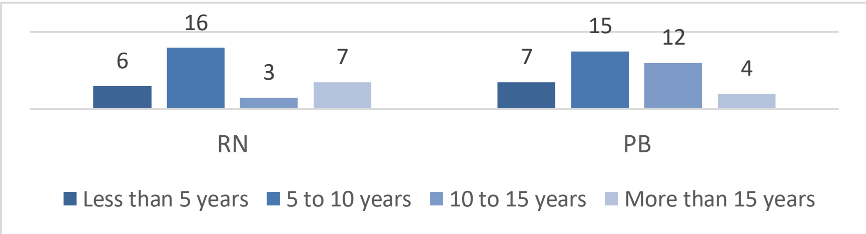


Figure 2: Professional experience (years)

## 4.2 Organization profiles

To draw the profile of the companies from Rio Grande do Norte and Paraiba, the questionnaire also sought to know the activities that they normally performed, in addition to the size and local scope of operation of the organization. As for the activities, the multiple-choice question with the possibility of more than one answer was used and the option to add an activity not mentioned was given. Figure 5 presents these results.

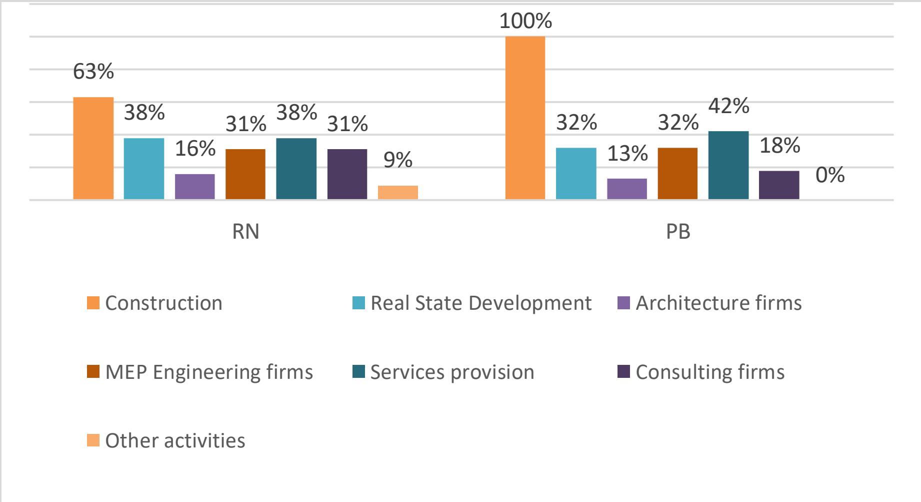


Figure 3: Activities performed by the companies

As for the size of the company, the analysis was made by the number of employees hired. It was considered a micro construction company with up to 19 employees; small construction company with 20 to 99 employees, medium construction company with 100 to 499 employees, and lastly large construction company with 500 or more employees. As shown in Figure 6, most companies classify themselves as micro or small.

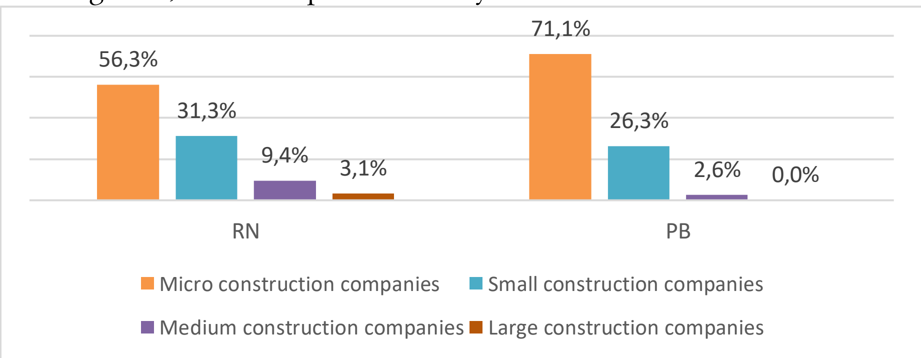


Figure 4: Companies size

Regarding the site operation of the companies, Figure 7 shows that a large part of their activities is local.

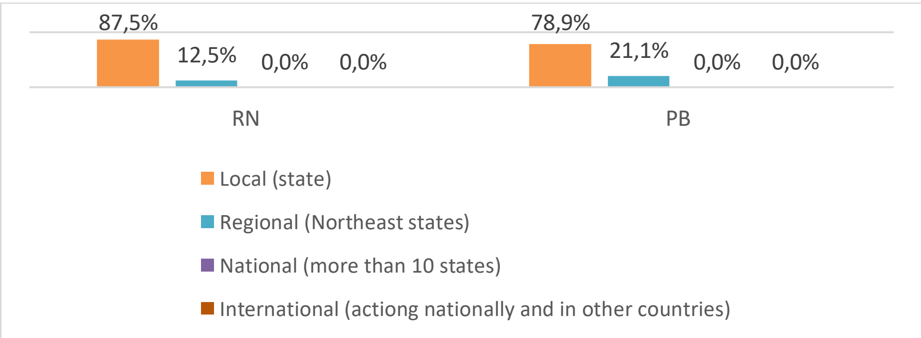


Figure 5: Activity places of construction companies

Figure 8 presents the annual business revenue reported by respondents. The capital in about 60% of the companies don't reach US$ 238.095,24. Considered the American dollar exchange of January 2020: US$1,00 (dollar) = R$4,20 (Brazilian real).

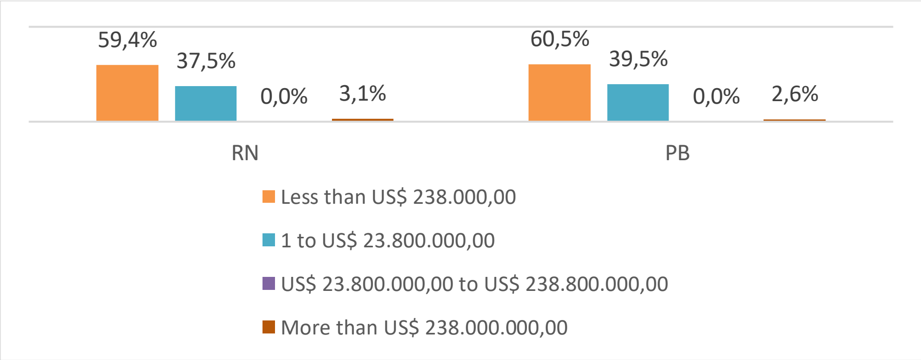


Figure 6: Business anual revenue

The Brazilian real estate market has lived through the last decade of great dynamism and has gone through two quite distinct phases. First, following the country's booming economic cycle, it experienced strong growth and registered the peak of prosperity. However, with the slowdown in the Brazilian economy starting in 2014, it entered a significant downward curve, which has caused construction sector to shrink dramatically.

According to Brazilian Institute of Geography and Statistics (IBGE) data, since the recession began in the second quarter of 2014, construction activity has shrunk by 21%. In order to identify how much the companies were affected by the national economic crisis, questions were included in the questionnaire asking how many projects were in progress or under development in the period before and after this adversity. Figure 9 presents the level of damage to companies caused by the crisis. Only 3,1% in RN claimed to have had no capital loss.

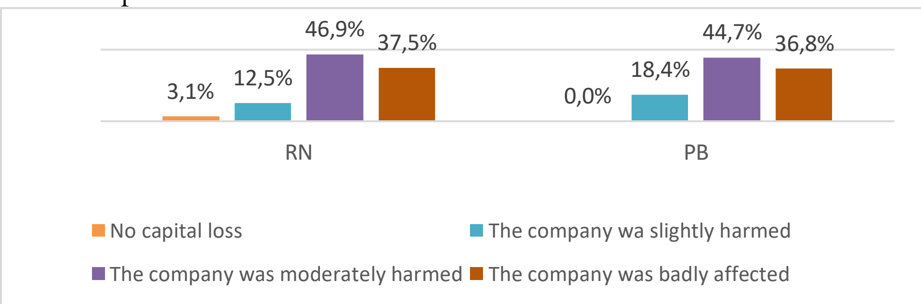


Figure 7: Intensity of injury caused by the economic crisis

## 4.3 Knowledge on the BIM term

The respondents were asked about their familiarity of the BIM term. For those who answered as not knowing what it means, the term was defined, and it was once again questioned if they understood it after the explanation. If they said “no”, they would not be able to complete the questionnaire. Figure 10 expresses the first question; and after explanation to those who answered “no”, 100% of them answered to be familiar in both states.

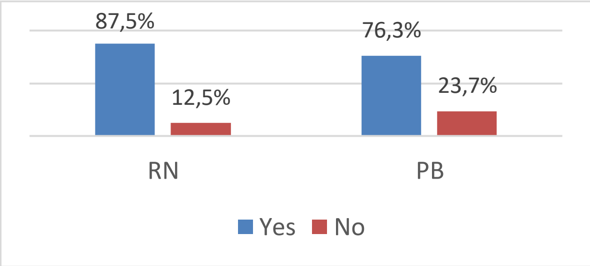


Figure 8: Familiarity with BIM term preceding explanation

After this procedure, it was investigated the professionals' personal positioning in relation to the BIM methodology through the multiple choice question exemplified in Figure 11. The companies of Rio Grande do Norte slightly stood out in relation to Paraíba both in the spontaneous question of familiarity with BIM and in the question of intent to use BIM and improvement in the near future (100%).

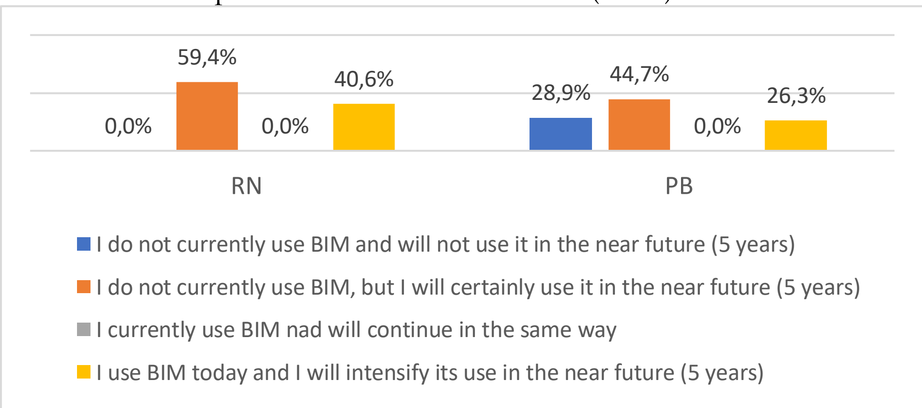


Figure 9: Personal positioning in relation to BIM

## 4.4 Characterization of BIM utilization

Then, the questionnaire sought to understand the implementation of BIM in companies, which is expressed in Figure 12. It shows that the negative answer is the majority in both states (62,5% in RN and 73,7% in PB).

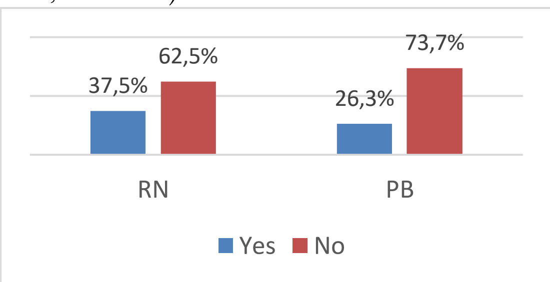


Figure 10: Companies using BIM

The BIM uses in companies that responded positively are present in Figure 13, establishing the 3D Modeling of Architecture and Project Compatibility as the main uses in Paraíba and Rio Grande do Norte.

Nine categories were presented (3D Architectural Modeling, 3D Structural Modeling, Collaborative Design on the same platform, Quantity Take-Off, Design Coordination, Clash Detection, 4D Modeling (Phase Planning), 5D Modeling, and 6D Modeling

(Sustainability Analysis) with the possibility of more than one choice and insertion of a new category, but 3 of them (4D, 5D and 6D Modeling) received no answer.

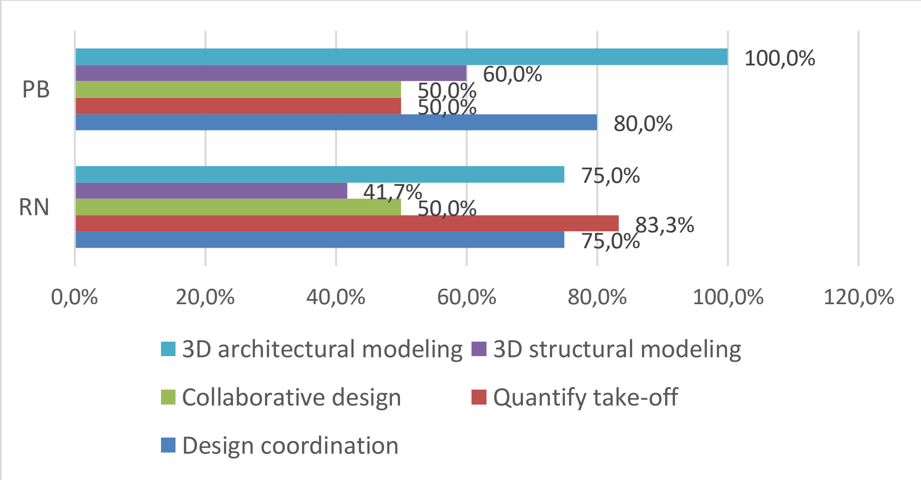


Figure 11: BIM activities used in organizations using BIM (percent)

Another question for those who already use BIM asks respondents to choose the statement that best approximates their reality, which best defines the way activities are performed. From the results shown in Figure 14, the only alternatives marked were A and B, which means that all BIM activities are done within the organization itself in about the majority of companies in both states.

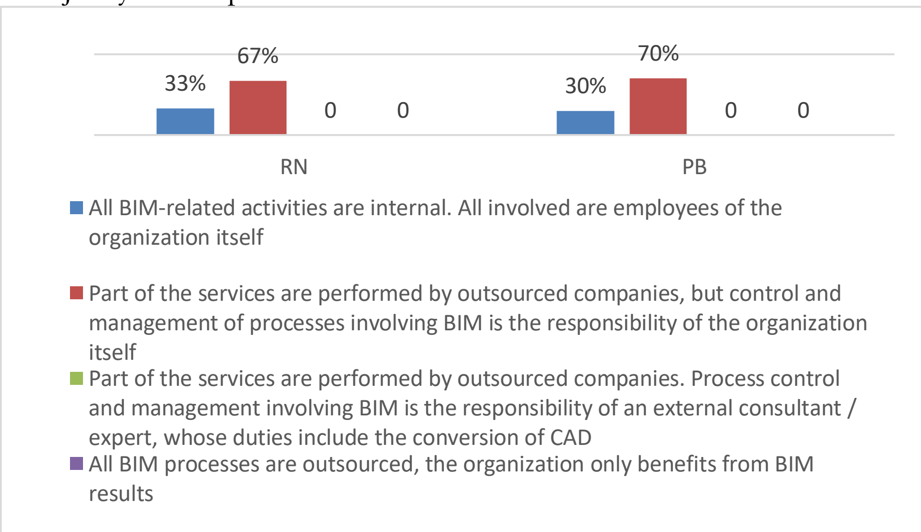


Figure 12: Characterization of BIM activities by companies

Moreover, Table 2 shows that most of these organizations (80% in PB and 83.3% in RN) see positive or partially positive results in the implementation of BIM, although 20% and 17.6% have not perceived or measured any benefits.

Table 2. Results of BIM utilization

| Results | RN | PB |
|---|---|---|
| Positive | 58,3% | 50% |
| Partial | 25% | 30% |
| Not measured or perceived | 17,6% | 20% |

## 4.5 Difficulties in implementing BIM

A series of questions was asked about the difficulties faced in adopting BIM for those who have already done so, or the reasons that prevent this process change from being made for those who have not yet done so. It was listed 9 topics considered in the literature as barriers, with an option to answer 0 to 3, indicating none (0), little (1), much (2) and maximum (3) relevance. Results are presented in Table 3.

Table 3. – BIM implementation difficulties by level of importance (percentage)

| Difficulties | RN | | | | PB | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 0 | 1 | 2 | 3 |
| Ignorance/lack of information about BIM | 12,5 | 25,0 | 37,5 | 25,0 | 18,8 | 42,1 | 28,9 | 10,5 |
| Little importance given to BIM by organization and/or project leaders | 5,6 | 18,8 | 37,5 | 28,1 | 21,1 | 36,8 | 39,5 | 2,6 |
| Lack of specialized internal (organization) labor | 9,4 | 12,5 | 34,4 | 43,8 | 5,3 | 23,7 | 34,2 | 36,8 |
| Software complexity | 25,0 | 31,3 | 34,4 | 9,4 | 18,9 | 29,7 | 40,5 | 10,8 |
| The value of software licenses | 12,9 | 6,5 | 35,5 | 45,4 | 5,3 | 5,3 | 36,8 | 52,6 |
| The cost of the IT infrastructure | 18,8 | 18,8 | 34,4 | 28,1 | 7,9 | 28,9 | 44,7 | 18,4 |
| BIM is not required for the market | 18,8 | 34,4 | 21,9 | 25,0 | 23,7 | 31,6 | 26,3 | 18,4 |
| External designers that the organization works with don't use BIM | 9,4 | 9,4 | 31,1 | 50,0 | 7,9 | 5,3 | 26,3 | 60,5 |
| Difficulty in coordinating the various project fronts and steps involved | 25,0 | 15,6 | 31,3 | 28,1 | 26,3 | 39,5 | 26,3 | 7,9 |

For both states, the most critical aspect is that external designers do not use BIM. For this, option 3 was selected by 50% in the RN and 60.5% in the PB.

In RN, the factors that were considered having the most relevance are the cost of software licenses (81.3%), external designers with whom the company works use BIM (81.3%), lack of skilled internal labor (78.2%), lack of knowledge or little importance given to BIM by organization leaders (65.6%) and cost of necessary IT infrastructure (62.5%).

In PB, the points considered most critical were similar to those of RN'n, except for the lack of knowledge or little importance given to BIM by the organization's leaders. Apart from that, the highlight was the value of software licenses (89.4%), external designers with whom the company works do not use BIM (86.8%), lack of specialized internal labor (71%) and cost of IT infrastructure required (63.1%).

## 4.6 The BIM future

The last questionnaire section was about the BIM future. Firstly, it was asked if the respondents believe if BIM will ever replace CAD. Results are shown in Figure 15. Only in Paraíba there is no expectation of this change occurring.

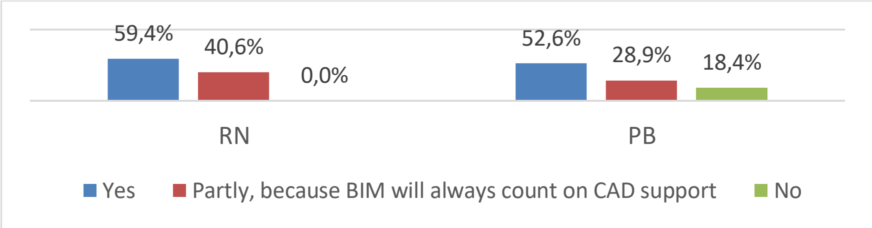


Figure 13: Thoughts on replacing CAD with BIM

Finally, it was asked about the approximate period for a possible standardization of BIM in the market. Figure 16 shows the answers obtained on this question.

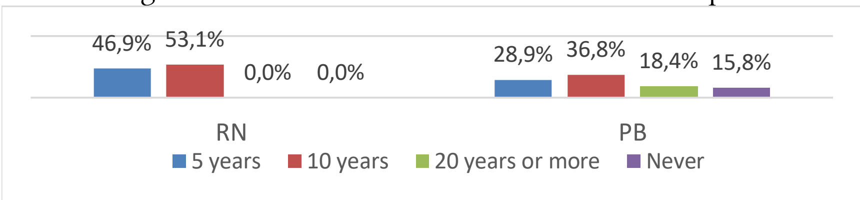


Figure 14: Expectation on BIM becoming industry standard

While in PB 15.8% of the companies believe that BIM will never become standard in the market, the state of RN stood out in highlighting a maximum period of 10 years. This may reveal more favorable trends for the use of BIM in this state.

## 4.7 Free manifestation of respondents

Concluding the questionnaire, respondents could comment on anything they thought relevant to the BIM discussion. No comments were made by PB, but ten people from RN spoke about it.

One professional reported that he has studied and used BIM since college and has also been a fellow in a BIM implementation program at the Infrastructure Superintendence of the Federal University of Rio Grande do Norte (UFRN) and a teaching assistant in the BIM course at UFRN (2010-2012). However, when he graduated, he experienced a lot of difficulty, especially since none of the structural and MEP designers he worked with use or even know about BIM. In his professional experiences, he developed an Architecture BIM Model, and then it was necessary to export to CAD for the development of MEP designs, making the design process considerably more laborious.

A second professional reported the similar frustration that many local companies already use the BIM platform, but end up regressing by having to export to CAD to collaborate with another professional or company responsible for the continuity of the design.

Many comments drew attention to the need to raise awareness of the importance of BIM, through the opening of more courses and training that can train professionals, and lectures that address the theme.

It was also mentioned that public agencies should give preference to designs made in BIM platform, due to their transparency and reduction of errors, resulting in more reliability in construction. For another person, the encouragement of the Federal Government through the BIM Dissemination Strategy is already influencing the market, as professionals are already more curious and willing to face the required procedural change.

## 5 CONCLUSIONS

The major contribution of this study is the characterization of the use of BIM in the states of Rio Grande do Norte and Paraíba, both states of the Brazilian northeast region, which was not covered in previous studies. Even through positive outcomes, BIM use is not a majority in both of them and it faces a number of obstacles, such as the cost of technology, lack of skilled labor, or issues of personal interest by Architecture, Engineering and Construction industry.

If the regional analysis performed is conducted in multiple locations, it will allow the understanding of difficulties and particularities of BIM implementation in a more detailed way, which may contribute to its dissemination in Brazil. From these results, specific guidelines can be developed to address the difficulties encountered in each location.

This study presented as limitation the analysis of only two of the nine Northeastern Brazilian states. Future research could apply the questionnaire in other states, aiming to obtain more consistent data of this region, as it is also recommended to be conducted for other Brazilian regions. Consequently, parameters can be created to determine the precise level of macro adoption and maturity of BIM in Brazil.

It is noteworthy that the results obtained can generate numerous surveys, since the comparison between the various regions, or even neighboring states, which may present quite different realities. Moreover, questions can be explored individually. For example, as the questionnaire addressed the economic downturn, it is possible to investigate how much it has influenced the implementation of BIM, as some companies may have taken advantage of the reduced workload for training and capacity building or introduced technologies that optimize their processes.

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# PEOPLE, PROCESS, TECHNOLOGY IN CONSTRUCTION 4.0 - BALANCING KNOWLEDGE, DISTRUST AND MOTIVATIONS

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**Abstract:** Construction sector digital transformation is an ongoing task engaged by the urgent goals of a more sustainable, efficient and competitive industry. Construction embraces these challenges quite behind. Given its unique environment, the success of transformation actions is fundamental. People, process and technology are essential analysis dimensions of the productive chain and involved parties. The outcomes and success measurement of these initiatives require advanced insights in order to strategically target the actions.

The present research contributes with tools for improved approaches to digital transformation initiatives, providing a framework to perform assessments and obtain a streamlined awareness of stakeholder's perceptions, motivations and confidence regarding one or more supporting principles of the Construction 4.0 vision. The development was based on state-of-the-art viewpoint and analysis of specific digital transformation initiatives. The framework output assumes the format of a survey. This was circulated on the context of post-graduate training actions. The motivation was achieving, for a specific type of stakeholder and context, a global picture regarding digital transformation impressions in its dimensions.

The findings evidence that "Technological dimension" is, in general, more mature than the others, meaning that efforts must concentrate on people motivations and added value of the transformation at "process level".

**Keywords:** Strategy, Digital Transformation, Management, Success, Stakeholders

## 1 Introduction

Construction is one of the first businesses that humankind developed, and it continues to shape our daily life in unique ways (Forum, 2016). The relevance of the industry can be observed on the built environment and how it affects the society and the landscape. The CI - Construction Industry is therefore crucial at societal, economic and environmental levels (Commission, 2012). Due to or despite this relevance, the industry has changed few over the years, namely when compared with other economic activities. This situation has been studied in different countries (Egan, 2000) (Richardson, 2014) and it can be stated that it is a common and worldwide issue, rather than a situation from a

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specific geography or single country (KMPG-PMI, 2013). Construction productivity has been increasing performance over the years, but at a rate that is nearly four times inferior to the observed in manufacturing industries. This behaviour impacts not only the competitiveness, but mainly the sustainability at economic and environmental levels. Construction is ripe for transformation and Industry 4.0 drivers are envisaged as enablers towards a more efficient, sustainable and competitive sector, shaping its pace in a route to higher productivity (Sriram Changali, Azam Mohammad, 2015).

Industry 4.0 paradigm stem from the 4th industrial revolution, where digitalization and cyber-physical systems (Desruelle et al., 2019) follow earlier revolutions based on mechanization, electrification and automation, respectively (Turk, 2019). The European Construction Industry Federation wrote in its manifesto: "Construction 4.0 is our branch of Industry 4.0. We use this term to refer to the digitalisation of the CI." (FIEC, 2014)

Therefore the "digital transformation" process relies in technologies and methodologies to introduce digitalization on the value chains setting Digital Twins as the ultimate goal. The same vision is brought to the CI at all levels from products or tasks to facility or built environment levels (CDbb, 2019). In what relates to technologies, the ones presented in Figure 1 have been placed at the forefront for adoption within the CI (PwC Portugal, 2016) (Sousa, H.; Mêda, 2017).


Figure 1: Technologies/Main principles of Industry 4.0 vision (Sousa, H.; Mêda, 2017)

The enthusiastic movements towards digital transformation in construction must understand the unique environment of the sector, the main barriers and the structural characteristics that have been dragging down the innovation adoption rhythm. The Industry Agenda developed by the World Economic Forum summarizes in its Figure 4 some of the main construction characteristics and client context that make the industry unique (Forum, 2016). Some might argue that the industry will not be able to accelerate the pace, as it is required. Without neglect that it will always require more effort and more time to accomplish when compared with other activities, the digital transformation of the CI is feasible and fundamental for the countries' economies, for the built environment and for the natural environment, among others. Spearhead companies, incremental innovation and knowledgeable strategic approaches on implementation processes are essential to assure the success of the initiatives, the added value of the achievements and the stakeholders' confidence (Yagiz, Kartal, et al., 2018).

Construction 4.0 challenges have been explored, among others, following the PESTEL framework (Political, Economic, Social, Technologic, Environmental, Legal analysis) (Oesterreich & Teuteberg, 2016). This approach identifies the main aspects or feelings that stakeholders have when confronted with digital transformation topic in general. This base knowledge can evolve to an analysis more detailed or focused on the activities of the value chain; the processes. This uses two dimensions of the PESTEL framework and adds a third to achieve the innovation imperatives or dimensions proposed by IDDS research roadmap (Owen, 2013). A value chain activities approach is found to be relevant as it provides maturity impressions, readiness model and defines how balanced the dimensions must be in order to strategically draw implementation processes towards the goals/success achievement in a specific initiative.

Digital transformation research activities and reports on implementation processes have been following this approach. BIM adoption strategies dominate the literature due to the relevance and impacts for the industry (Succar & Kassem, 2015) (Hjelseth, 2017). Collaborative tools (Derenzi et al., 2009) (Martin Fischer, Howard W. Ashcraft, Dean Reed, 2017), 3D printing and more recently Blockchain technology (Ali & Smith, 2019) are other relevant topics, just to name few.

The evidenced gap between implementation strategies and stakeholders motivations can lead to failure. Worst, is the mind set and preconceptions that stakeholders quickly spread and add to their always existing resistance to change (Calvetti, et al., 2019) (Fischer, et al., 2017). The motivation for the present research comes from the daily challenges in raising the bar of the industry towards the adoption of innovations and from the experience of managing digital transformation processes at large scale in a public institutions (construction owners) ranging the construction process from design until end construction and linking with facility management. The process was continuous during 3 years and had a successful implementation (Sousa, H.; Mêda, 2016). The initial strategies targeted for technological aspects were rapidly shifted to personal and process based strategies. The technological dimension was introduced as a problem solver and a way to streamline processes and fulfil requirements (new and existing ones that were not accomplish on projects) (Rasmus Rempling, Esra Kurul, 2019). The lessons learn from this experience raise on the team the awareness for the "fineness" of achieving successful digital transformation processes in the CI.

## 2 Research objectives and contributions to the Body of Knowledge

Higher competitiveness, sustainability and efficiency are goals for the CI. Digitalization, as stated, is a megatrend and a driver towards those objectives. How can companies and stakeholders take the best steps and the best advantage from the implementation of new technologies in order to accomplish their own goals and the industry challenges?

The digital transformation of the CI is more sensitive than in other economic activities due to its unique environment, specificities and broadness (Forum, 2016).

The research frames on the difficulties on achieving the best benefits or at least a successful evaluation of these processes. Every effort to implement new technologies or processes must be strategically defined and targeted for the added value that can bring to the industry at personal, corporate and construction process levels. In addition, the innovative actions cannot bring more effort to the stakeholders, namely if this relies on the manual introduction of the same data in different tools. A less successful implementation of innovations can promote severe preconceptions and mind sets that will become very difficult to overcome. The introduction of innovation processes must rely on approaches that evaluate dimensions as People, Process and Technology. The success or failure of the process depends on the delicate balance of these aspects in accordance with the stakeholders and companies involved.

The objective of the research is to raise awareness for the sensitivity on the preparation of innovative actions that contribute to the construction digital transformation and provide tools to support and obtain, at early stages, an improved awareness of the perceptions, preconceptions, doubts and weaknesses of the stakeholders facing the process. This information is found to be extremely useful as decreases the gap between the technology to be implemented/adopted and the adopters. The development of knowledgeable strategic approaches can contribute to the success rate improvement of digital transformation processes in the CI.

Despite the fact the outcomes impact all industry stakeholders, these are assumed, at this point, to be more relevant to Corporate Directors, Managers and Consultancy in Innovation, to gain awareness and define the best roadmaps and strategies regarding the positioning of a company, its objectives and best select the early adopters or the "transformation team".

## 3 Methodology

The sensitivity of implementing innovative actions in construction is not a new subject and, as stated, many authors have been addressing their studies to this topic. Yet, many are more focused in specific technologies or methodologies. The state-of-the-art viewpoint allowed the identification of references to constitute a background for this broad approach.

The objective was to achieve a global perspective of stakeholders facing CI digital transformation using as starting point Industry 4.0 main technologies. Consequently, a review on strategic documents towards Industry 4.0 and Construction 4.0 was required.

These were combined with the “Imperatives” or dimensions of the IDDS research roadmap to enable/foster a multifaceted opinion of the stakeholders regarding a defined technology and perceptions of its usability both by people in construction, as well as a tool to support construction processes/tasks across the value chain.

To achieve organized and compiled data the framework was transposed to a survey. This is composed by two parts. The first is where respondents select for each technology at “technology”, “process” and “people” dimensions the maturity in accordance with a four scale option: “1- Emerging; 2-Sedimented; 3-Generalized; 4-Consolidated”. This provides the maturity levels for each technology in each dimension. The second part is composed by an essay question where respondents select and develop an explanation of the reasons, motivations and visions/opinions that led to the identification of the maturity levels on the previous question. The challenge was to select and develop justification for two technologies.

The survey provides both global and detailed vision of stakeholder’s opinions/knowledge regarding digital transformation technologies.

The questions and schema of the survey are presented in the following section. To test the framework and perform a first analysis of the potential results, the survey was used as part of the activities of a post-graduate training action delivered using e-learning.

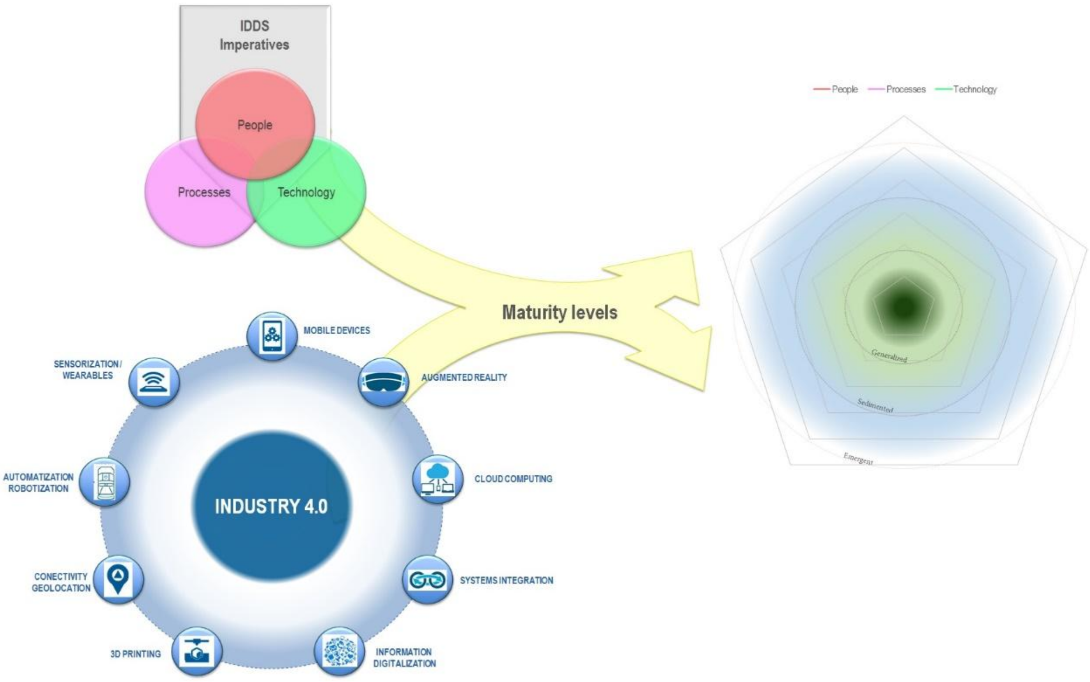


Figure 2: Elements and their combination to achieve the visual outcome of the framework.

# 4 DEVELOPMENT

## 4.1 Survey

As presented in Figure 2, the framework comes from Construction 4.0 main technologies combined with IDDS innovation dimensions and four maturity levels established for the purpose of the survey, providing four possible selection fields. The first question aimed quick and broad stakeholder's opinions regarding the technologies, its use in construction processes and knowledge/empathy of these technologies at a personal level. The question and table are the following:

*"For an innovation process to succeed it is necessary to find a balance between dimensions such as technology, processes and people. Construction sector digitalization megatrends are based in some technologies. The purpose of this question is to understand your personal view as construction stakeholder of the maturity of different technologies in the industry, the maturity of their use in construction processes/tasks and the knowledge/empathy of the construction stakeholders for their use. Identify for each situation the maturity level that fits better your vision."*

The second question is an essay where an introduction/guideline is presented to exemplify the type of intended answer. "Mobile devices" technology was used as example because it was found to be the one that could be easily understood by all students.

*"Following the development of the previous table, perform an essay based on one or two technologies (other than mobile devices) where you detail the reasons for selecting the*

*maturity levels in the different dimensions. The text above exemplifies the type of intended answer:"*

*"In terms of technology, the opinion is that "mobile devices" have a "Consolidated" maturity, as most of the construction industry stakeholders use mobile phones, tablets, others, on a daily basis either for work or personal purposes. People have empathy to the mobile devices and, at personal level, there is a "Generalized" maturity regarding the knowledge on the basic tools and their use, namely phone, agenda, camera, Internet access. The use of mobile devices to support construction processes is the dimension that is less mature. There are several applications (apps) and mobile devices functionalities that are already used to support construction processes. Yet, the range and full potential of these devices for the processes in construction have still a lot to accomplish. Given this, the maturity at process level can be considered as "Emergent"."*

Table 1: Table for respondents to mark their opinion in terms of maturity levels

| Technologies/Dimensions | Maturity | | | |
|---|---|---|---|---|
| | Emergent | Sedimented | Generalized | Consolidated |
| TECHNOLOGY | | | | |
| Mobile devices (smartphone, tablet, others) | | | | |
| Augmented Reality | | | | |
| Cloud computing | | | | |
| Systems integration/interoperability | | | | |
| Information digitalization / metadata | | | | |
| 3D printing | | | | |
| Connectivity | | | | |
| Automatization/Robotization | | | | |
| Sensorization/Wearables | | | | |
| PEOPLE | | | | |
| Mobile devices (smartphone, tablet, others) | | | | |
| Augmented Reality | | | | |
| Cloud computing | | | | |
| Systems integration/interoperability | | | | |
| Information digitalization / metadata | | | | |
| 3D printing | | | | |
| Connectivity | | | | |
| Automatization/Robotization | | | | |
| Sensorization/Wearables | | | | |
| PROCESSES | | | | |
| Mobile devices (smartphone, tablet, others) | | | | |
| Augmented Reality | | | | |
| Cloud computing | | | | |
| Systems integration/interoperability | | | | |
| Information digitalization / metadata | | | | |
| 3D printing | | | | |
| Connectivity | | | | |
| Automatization/Robotization | | | | |
| Sensorization/Wearables | | | | |

This example of essay was just to express one opinion and the maturities were defined based on authors feelings and knowledge with the consciousness that it could influence some of the results, namely in terms of this technology. This was one of the other reasons to perform a guideline essay using mobile devices and not any other technology.

## 4.2 Case Study - Samples

As mentioned, the results were obtained through the development of surveys that circulated as part of the activities of a post-graduate action in construction management specially designed for architecture and engineering professionals. This action was structured by the institutions where the authors belong and it was delivered mainly to Brazilian professionals. The first action took place in 2018 and the second on the following year. There were 52 and 45 valid surveys, respectively, performing 97 answers. This sample, despite the considerable dimension, is narrow, when compared to the size of the Brazilian CI and its stakeholders.

Nevertheless, the results, as detailed further, are found to draw a very good picture of the awareness and perceptions of this group of stakeholders (design team members, managers and construction/field directors – architecture and engineering professionals (Desruelle et al., 2019)) regarding the digital transformation of the industry.

As part of the survey, the essay or detailed explanation was asked to all students in order to obtain more insights. This information is found essential to have a more clear perspective of stakeholder's knowledge, understanding and feelings. The next sub-section presents an analysis of the results and is supported with the transcription of some answers.

## 4.3 Results

Given the opportunity to work with two samples with similar characteristics, same country, same type of stakeholder and similar size, it is possible to perform analysis at different levels. Therefore, this part explores the results of each survey individually and to what is found to be the best balance between the different dimensions for each technology. In parallel, insight is performed regarding the most mature technologies, when facing a direct comparison process. Respondents' visions were used to support some of the results. The section "Discussions and Findings" will concentrate more on a global vision of the results from the two surveys, setting a way for the conclusions where future headings are explored. Figure 3 systematizes the results of the 2018 survey.

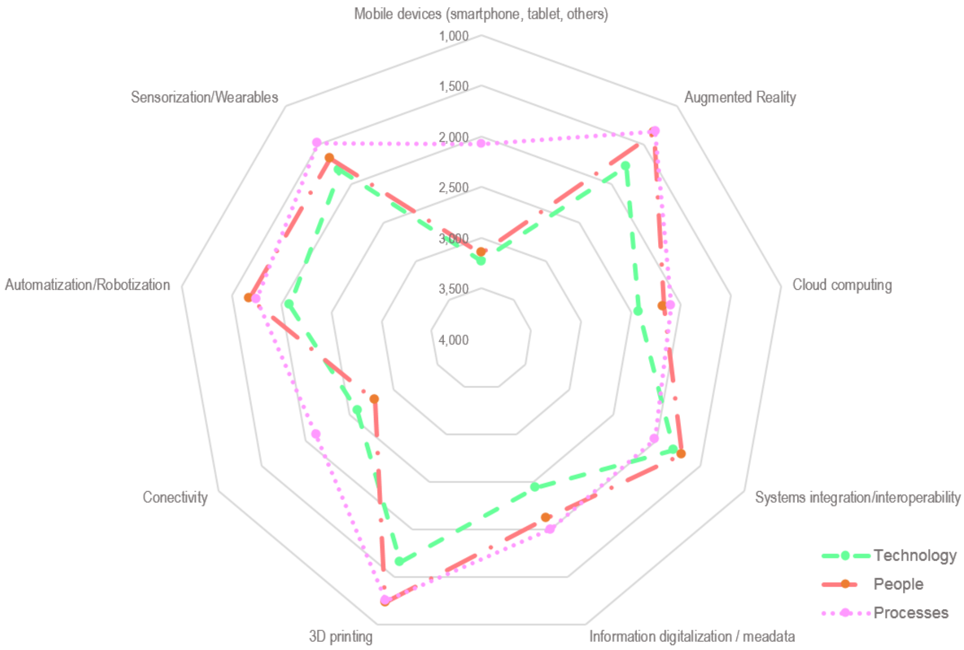


Figure 3: 2018 survey results

As it is possible to observe, the technology that evidenced high maturity in terms of the "technological dimension" is "Mobile Devices", followed at distance and with similar results by "Connectivity", "Information digitalization" and "Cloud computing". "3D printing" is the technology that registered a lower maturity level, not only in the "technological dimension" but also in others and is closely followed by "Augmented Reality". Insights from respondent's essays detail the reasons for these results. Influenced or not by the example presented on the survey, "Mobile Devices" evidences at "process dimension" a significant lower maturity level when compared with the other dimensions. In fact, this is the technology where the highest maturity gap is observed between the different dimensions. In opposition, "Systems integration/interoperability" is the technology where the three dimensions evidence less deviation.

In most technologies, the "technological dimension" is ahead of the others, exception made for "Systems integration/interoperability", where the "process dimension" is found to be the more mature and for "Connectivity" where "personal dimension" registers the higher maturity.

These cases find interesting justifications on the type of stakeholders' that answered the survey. Architecture and Engineering professionals are skilled and knowledgeable of the impacts that "Systems integration/interoperability" have in their value chain processes. The technologies to accomplish are still lacking in fulfilling all the aims. Digital transformation strategies, at this level, should use processes knowledge to help drawing improved technological solutions. "Systems integration" is a subject that always raises issues related with resistance to change (Fischer, et al., 2017). Therefore, the achieved results for the "personal dimension" are far from being strange. Given this picture, the implementation strategies must approach "People" from the "Process" side, working misunderstandings, reluctances and fears.

The opposite is evidenced with "Connectivity". This can indicate that at "People dimension" the stakeholders' know and deal well with the technology, in part because it is partially embedded in "mobile devices" (the results are similar at people dimension), but when it comes to use it in construction processes there is a lack of understanding of the applications. The approach should focus then on the processes where this technology can be used. Two examples of respondents' essay on the above mentioned technologies help to support the visions:

*""3D printing" is a very well-known technology in Brazil. Despite this fact, the scenario in terms of the construction industry changes. The notion is that is a promising technology with many potential applications both on large and small projects, as well as for the production of building/infrastructure parts. The feeling is that in a near future the use of this technology will increase significantly within the CI. Given this, and for the present moment, I find "3D printing" "Sedimented" at technological level given the influence and knowledge from other uses outside construction. At People and Process level the technology can be considered "Emergent" as the uses, applications and knowledge stills lacks. Stakeholders are concerned, at the moment, with tools to support other processes."*

*""Augmented reality" is still an "Emerging" technology, namely at people and process levels. The technology is known from other sectors, namely entertainment and gaming. "Augmented reality" in the CI can have many different applications, most of them glued to an advanced visualization of BIM. This means that in order to become more used it has to be integrated with BIM and follow up its implementation that it is still not widespread. Its use in construction is at the moment narrowed to sales and marketing processes but few companies are running it due to the required investments."*

The 2019 survey results are systematized in Figure 4. The sequence of the three dimensions in each technology is the same registered in 2018 with exception to "Systems integration/interoperability" where the "process dimension" is surpassed by the "technological dimension" and "Connectivity" where the "technological dimension" falls behind assuming the position of the less mature dimension.

It is interesting to highlight that these exceptions occur in the technologies where in 2018, the "technological dimension" was not the one where higher maturity was registered. The deviations between the dimensions are in general lower in the 2019 survey and the lowest was registered in "Augmented Reality". The results of the essays' on this technology are therefore interesting to explore as it follows:


Figure 4: 2019 survey results.

*"It is my feeling that "Augmented Reality" is evolving and expanding rapidly. This technology is being more and more adopted to support the design process as it allows professionals to take advantage of the visualization potential to identify problems prior to construction, allowing their correction. This streamlines and speeds up the construction stage as well as contributes to the quality of the final product. At "people level" stakeholders understand that this is a tools that raises efficiency and supports decisions. Interfaces and training for improved design processes are key."*

From this answer it is possible to identify a shift on the main uses of this technology. In addition to marketing and sales "Augmented Reality" gains relevance as a tool to support improved design processes.

In opposition "3D printing" is the technology where higher dispersion between the three dimensions was observed, namely if we compare "People and Process" dimensions (nearly the same maturity; barely "emergent") with "Technology" dimension that is considered "sedimented".

Again, due to this results it is interesting to look in detail to the respondents essays on this subject, namely the ones that add some to what was stated on the 2018 survey:

*""3D printing" is a technology with many applications in several economic activities. This promotes a broad knowledge of its potential uses, even within the construction. Therefore, the knowledge can be considered "sedimented" at "technology" dimension. The implementation costs are high and require a reconfiguration of processes and practices. This is the experience from other industries and construction will be no exception. And this can be the main obstacle and a reason to consider that at "people and process" dimensions the maturity is still "emergent". There are large applications off-site and integrated on scientific experiences, yet, on site it will be challenging on the following years as processes and practices are fragmented and diverse. Situation might change if the technology cost decreases and small companies appear providing specific advanced construction services or solutions using this technology."*

“Automation/Robotization”, “Sensorization/Wearables”, as well as previously mentioned "3D printing" are the technologies where it can be observed at “people and process dimensions” the lower maturity levels. This can find justification with the concerns and role of the inquired stakeholders’ on the construction value chain. This can be confirmed again looking to the essay answers and respondents profile. Without placing a single translation of one answer and considering answers overview, there are some respondents that address to these two technologies, mainly if they have a role during construction, namely field director. One of the most interesting answers stated that the fragmented value chain of the construction industry, even at activities level, prevents the generalization of "Automation/Robotization". A field for this technology in construction might come with the advances of autonomous vehicles and the adaptation to site equipment's. And this is one interesting touch-point with "Sensorization/Wearables" as some essays state that the use of this technology is more mature outside the industry where people use sensors combined with other technologies for daily purposes, as running or others. Notwithstanding, the use of sensors by field equipment's and workers to control their position on site (safety issues) is identified as the gateway for the implementation of the technology within the industry.

## 5 Discussion and Findings

The results from the two surveys evidences an alignment that surprised the authors. In all technologies and for the three dimensions it was observed, in terms of maturity, the same results or evolutions. One single exception worth’s to be highlighted that is the “people dimension” in “Sensorization”. This registered a slight setback that can be justified with the type of stakeholder that answered the survey.

The evolutions can be considered natural and reveal that awareness actions on digital transformation are taking effect in particular for the case of this type of stakeholders.

The survey results can be highly influenced by the type of stakeholder, meaning that different technologies will reveal different maturity levels at all dimensions depending on the role.

A situation that worth's to follow up is the behaviour of the results within the same type of stakeholder but facing different contexts, namely countries.

Architecture and Engineering professionals are found to evidence more knowledge/concern for some technologies. The results express that “Cloud computing”, “Information digitalization/metadata” and “Connectivity” are the technologies where in all dimensions the maturity levels are higher. Follows “System integration/interoperability” and “Augmented reality”. One identifiable reason for these results can be the fact that these technologies are closest to the respondent's daily processes. Respondents' essays confirm this statement as many state that "cloud technologies" are daily used to share documents and applications at different stages of the construction process. This type of technology also fosters mobility as the same person can have access to documents in different places and using different interfaces (PC, mobile, tablet, others).

When looking in detail for the perspective of each technology, it is possible to see that the readiness and the implementation strategies must vary and meet the stakeholders’ feelings.

The dimension that evidences less maturity is the one that will lead the entire strategic design of the digital transformation process. Through the understanding of the why it is possible to set a roadmap and milestones to overcome step by step the difficulties, improving the chances for positive outcomes.

The results provide a clear vision on the evolution of the awareness process and on the strategies to adopt on digital transformation processes for the target group of the survey.

## 6 CONCLUSIONS

Digital transformation is not an end, but a powerful mean to accelerate the recovery of the CI. Implementation processes will always be painful, laborious and require a commitment from all parties involved.

To accomplish the goals of digital transformation in construction it is necessary to achieve the success at all levels on the highest number of implementation processes. Empathic technology, well embedded on the construction processes that deals with, streamlining them and obtaining the best from its users in terms of work power and motivation is a continuous challenge to have in mind. In addition and prior to start, strategic thinking using frameworks as the one presented must be established to assess the stakeholder's readiness and feelings towards the process. These can also be used for the process follow-up, working as success enablers.

Setting an overall digital transformation strategy to this group of stakeholders based on the combined results of both surveys, the first actions should aim increasing the maturity at "process dimension" in "Mobile Devices". In parallel, concerns should focus on increasing the maturity at all dimensions in "Connectivity" using an approach based on "process" dimension, this is, evidencing the processes in construction where this technology can be applied. Second level actions should work "Cloud computing" and "Information digitalization/metadata". "Systems integration/interoperability" and "Augmented reality" constitute a third action level as the second mentioned technology can benefit from high maturity levels at all dimensions of the first one.

The developed framework positions at a medium level. It is narrow than PESTEL analysis but provides broader results than dedicated strategies. Notwithstanding, it can be used either for a global/meso perspective on a group of technologies or focus on a single technology working individually the results of the distinct dimensions. The survey allowed the validation of the framework and more, as the outcomes prove to be valid for strategic approaches within the context of the respondents (country and type of stakeholder).

The next-steps will focus on answering some of the questions raised in the "Discussion" part as well as drawing strategic approaches for real implementation situations of one or more technologies using the results as guidelines.

The improvement and focus of the framework on specific topics is envisaged for the purpose of certain roles in the industry. One specific example are the cost engineers, top managers of construction companies and some BIM roles, where background and other frameworks have already been developed and tested. The same type of respondents in other countries constitutes also a future heading to evaluate the differences.

## 7 ACKNOWLEDGMENTS

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# MANAGEMENT PROCEDURE FOR SENSITIVE PROJECTS IN THE CONTEXT OF A BIM ADOPTION IN A PUBLIC ORGANIZATION

**Giuseppe Miceli Junior[1], Paulo C. Pellanda[2], and Marcelo C. Reis[3]**

**Abstract:** The increasing adoption of Building Information Modeling (BIM) in the management of Architecture, Engineering and Construction design processes has intensified digital information among stakeholders. If strategic and sensitive projects are developed for the public environment, BIM deployment must have additional characteristics. This paper aims to propose processes for project planning management, applying it to a public organization that has its own project teams for the development of military projects. It is based on the adaptation of ISO 19650-1 and ISO 19650-2, which standardizes the creation, management and use of information contained in models, and the design of ISO 19650-5, which standardizes security-minded procedures for models and digital built environments. Activities within all procedures were summarized in three main management groups that have shown to be interconnected: management of the model with information security procedures, product management and the public governance management. The processes were then evaluated in a sensitive design, in respect to their applicability in a design office. As a result, while product and governance management groups have increased its efficiency with BIM implantation, model management still takes time to present optimum efficiency, thanks to little knowledge of BIM professionals in sensitive aspects of the project.

**Keywords:** Collaborative Design, Building Information Modelling, Sensitive projects, Public organizations.

## 1 INTRODUCTION

Project is generally understood as the temporary effort with the intention of creating an exclusive product, elaborated progressively in stages, being submitted to planning, execution and control (PMI,2015). The information flow during project development has become more intense, making necessary to develop Information and Communication techniques in order to manage the increasing flow and, at the end of the project, to meet their demands.

Building Information Modeling (BIM) is defined as a set of associated technologies, processes and policies to produce, communicate and analyse constructive models, enabling stakeholders to collaboratively design, build and operate a facility (Succar,2009; Eastman et al. 2008). Around the world, BIM has been successfully applied worldwide by companies and organizations; being a common practice in design process in countries

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like Sweden, Australia, China, the United States, the Netherlands, Finland, Norway and the United Kingdom (Gu et al. 2011; Cheng and Lu, 2015).

However, many organizations still tend to believe that having a modeling software to produce design models is enough to practice BIM, restricting its benefits to the purchase of a 3D modeling tool. Other organizations tend to buy several software suites that have got little interoperability among them. One can tell that any BIM adoption centered only in technology field has little chance of success.

This work aims to develop a management procedure in the context of a BIM adoption in a Brazilian public organization, applying it in one of its design offices which develops its own sensitive projects. In this way, BIM adoption must contemplate some requirements in respect to information security, submission to public compliance and specific project conditions.

# 2 LITERATURE REVIEW

## 2.1 Management actions in BIM adoption

BIM adoption in public environments is generally based in several sets of factors that may influence its outcomes, but in a different shape from those adoptions developed in private companies.

Some researchers (e.g. Manzione,2013; Pereira,2017; Souza,2016; Franca, 2016) developed conceptual structures where management actions in the building information model (BIModel) always have correspondence with product development phases.

In public organizations, however, BIM adoption must consider public governance actions, in order to support all actions related to model and product development. A public-partnership association may be mandatory for the success of the BIM implementation and design maturity (Porwal and Hewage, 2013)

Based in a previous work, Miceli Junior et al. (2019) classified all these factors into three groups of actions, describing the interaction among them in a tri-axial BIM adoption framework, illustrated in Figure 1 and better described in the next sections.

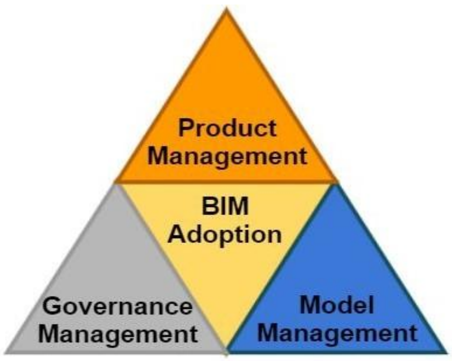


Fig. 1. Management groups in BIM adoption (Miceli Junior et al. 2019).

### 2.1.1 Model management.

Related to the use of BIModels in process management and all related specifications, including BIM adoption and its implementation effort in organizations. International standard ISO 19650 describes all concepts and principles regarding model management, as well as the description of all delivery phase of the assets. Until now, it is divided in two parts, with other two parts in final revision.

ISO 19650-1 (2018a) defines the concepts and principles regarding the information delivery cycle in all stakeholders' perspectives and design collaboration. On the other hand, ISO 19650-2 (2018b) defines information delivery process and divides it in eight phases that will be briefly explained:

- Assessment and need: With the definition of all rules, responsibilities and activities for information management with all necessary specifications and obligations.
- Invitation to tender: All information and requirements regarding to the information flow and its management must be defined and compiled in tender documents, so that the public or private market become aware of the bid process.
- Tender response: The bidding company should develop its own tender documents, based in the selection of the project team, assessing their capacity and ability (ISO, 2018b; Holzer, 2016).
- Appointment: At this stage, the contractor must confirm the pre-contractual BEP established by the winning bidder, establishing a post-contractual BEP including all BIM workflow guidelines (ISO, 2018b; Holzer, 2016).
- Mobilization: All processes, policies and technologies pre-established in the delivered BEP are tested by the contractor. (ISO, 2018b).
- Collaborative production of information: It is based on collaborative production, based on the modeling process itself, with high BIM tool interoperability and broad collaboration among professionals. (ISO, 2018b).
- Information model delivery: Consolidation of all project deliverables: documents, BIModels and all data produced. It is the phase where the contractor makes the final verification of the project model, concluding by its acceptance or not.
- Project close-out: Archive of the CDE and consolidation of all lessons learned for futures projects, including them in future adaptations of the PEB.

#### 2.1.2 Product management.

It is related to product adequacy to client technical specifications and compliance with deadlines and costs, as well as how constructions are designed by the design team.

Although there are different definitions and standards for which project phases exist, they generally follow a sequence. For example, Brazilian standard NBR 16636 divide project effort in a design preparation phase, including feasibility studies, preliminary and specific data collection and location definition; and a technical design development phase, including draft development and construction design itself (ABNT,2017).

The modelling process of all disciplines and the related federated BIModel are always developed by the project team, along with product management and great participation and aid of the team of BIM champions.

#### 2.1.3 Public governance management.

Related to the submission of all project effort to external governance and auditing rules in order to ensure and its accountability to citizens. In general, a public organization must always be accountable for its actions and expenditures, so BIM adoption processes must take this fact into account.

Unlike other two groups, governance management activities are not sequential, but all of them permeate the entire project process. Activities where governance tasks are paramount to ensure a good project development and BIM deployment can be summarized as follows:

- Demand of the organization direction for starting a new project.
- Requirements definition for project development, cost and schedule management.
- Provision of conditions for project team to develop the project (budget prediction and authorization for bidding).
- Definition of bidding processes for services and admission processes to select professionals necessary to enable design and product development.
- Bidding process itself and contract award.

A deep integration between product management (e.g. schematic design, full design) and model management activities (e.g. model evaluation, design model) is suggested through project process (Pereira,2017; Souza,2016). Unfortunately, in most countries, Brazil included, there is little legal support for non-DBB bidding and procurement process, so most BIM public projects, if not all of them, follow DBB pattern, failing to guarantee the integration.

## 2.2 Information security in sensitive projects

The main reference standard that deals with security information is British standard PAS 1192-5 (2015), in update process to the future ISO 19650-5 standard. It presents requirements for the management of projects developed in digital technologies, for information security in building information models, digitally built environments and intelligent asset management (ISO, 2019; BSI,2015).

Sensitive assets are those facilities that comply with diplomatic, security, national defense or law enforcement, or any facilities that may be used to compromise the integrity of the asset built as a whole or its ability to function (ISO, 2019). Also, according to this PAS, the specific attributes that considered as sensitive within a project minimally include location and data on:

- Control and surveillance systems.
- Permanent machinery.
- Control, access and security rooms.
- Cabling and installations related to previous systems.
- Structural design details.
- Technical product specifications and safety characteristics.

It is also established a sequence of activities with the intention of carrying out the project, through its execution and supervision the whole construction operation.

Activities start with a security triage process in order to determine whether a security-minded approach is required in relation to the project to assess the level of information safeguard that should be adopted, both in relation to asset construction and its neighboring assets. A security manager also should be appointed by the entrepreneur, who will be responsible for all advisory and security procedures to be developed thereafter.

Security-minded approach must be developed alongside a holistic view of the security threats and vulnerabilities that may arise in project process, everything involving all BIM fields: technologies, politics and processes (Succar,2009). From this point of view, security-minded approach shall be developed alongside the sequence described in ISO 19650-2.

After security triage process, a security strategy must be settled, including assessment of all specific security risks arising from the new level of technology involved in BIM adoption, the potential risk mitigation measures, a summary of the tolerated security risks and the review and update policies for the security strategy. It should include all personnel, physical, technological aspects, as well as the information security policies and process which will influence the BIM execution plan development (BSI,2015).

From the security strategy, a security management plan shall be developed by the organization, which will be also responsible for its maintenance and implementation. The plan shall contain all requirement related to the provision of information and to installation of any security assets and systems. A security breach/incident management plan shall be created and maintained (BSI,2015).

## 3 RESEARCH STRATEGY

Design Science Research was used in this research. It is a methodology that seeks to close the gap between the theory and the practice, working collaboratively with organizations to test new ideas in real contexts (Dresch et al. 2015).

The artifact developed in this research consists with the creation of a set of processes based in an adaptation from ISO 19650 and PAS 1192-5. All processes tend to be applied to a public organization, which has design offices spread throughout Brazil; each of these organization offices have its own design team and are also responsible for the lifecycle management of all facilities inside their occupation area.

For the development of the artifact, one sought to survey the current state of the BIM implementation in the organization, in order to know the starting point from which all BIM adoption efforts would begin.

Prior to project initiation, organization's processes were then studied, through face-to-face interviews and some reunions among the researcher and the organization professionals during the second semester of 2018. All reunions aimed to collect all data regarding all management processes related to design development.

The project which will be described in Section 5 has specific requirements, both for the BIM implementation and for the design development. Because of its sensitive characteristics, security measures related to design development of the BIModel were also studied. All processes were then divided intro the three management action groups defined in Section 2.1, also considering all necessary security measures for its development.

## 4 ARTIFACT DEVELOPMENT

Based in prior works about BIM implantation in public organizations (Miceli Junior et al. 2019), the artifact was developed by integrating the three management groups with security-minded measures, as shown in Figure 2. One can observe the governance management activities were initiated was the decision of the authority responsible for the construction of the work. That phase is followed by the definition of the construction plan for the current year and its consequent communication to all design offices.

The next phase within the governance process group, represented in brown boxes, is project planning. It directs all of project's upcoming planning efforts and It must provide all conditions for both BIM deployment and project development.

Based in initial project planning, all efforts to acquire the necessary resources (hardware, software, new network solutions, common data environment), contracting auxiliary services (topographic surveys, geotechnical surveys) and hiring of personnel (professional and technical personnel) are started and conducted based in well-defined bidding documents that have undergone prior legal analysis.

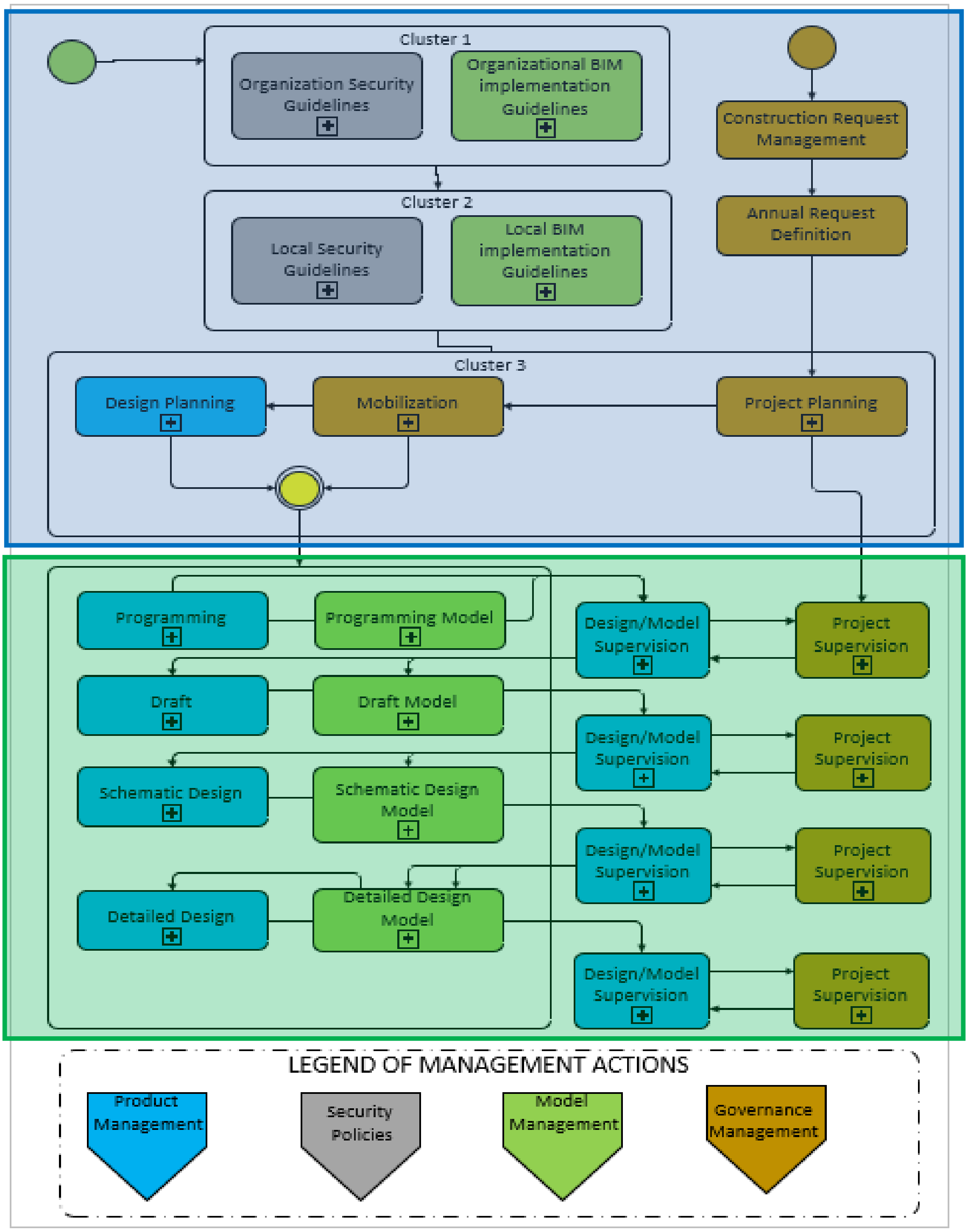


Fig. 2. Proposed framework for this research. Blue rectangle represents design planning phase while green rectangle represents design development with collaborative production of information.

In this work, model management actions, represented in green boxes in Figure 2, are split into two groups, where are defined all necessary organizational guidelines and local guidelines. In the other hand, product management actions, represented in blue boxes, guard a deep relationship with model management ones, partially because BIModel is always developed simultaneously to design: the more developed it is, higher are the level of development of construction components.

While organizational guidelines include the appointment of the information team and the definition of the conditions BIM would be adopted in the public organization, local guidelines generally include the appointment a BIM manager or an office information team and outlines how BIM will be adopted in the office. Example of local guidelines documents are the BIM implementation plan, the BEP, and the project execution plans.

All security measures related to BIModel creation, in this research, follow a defined sequence inspired in PAS 1192-5, being represented in grey boxes in Figures 2 and 3. Regarding a sensitive design project, they must be defined before project beginning and must guard a broad relationship with organizational and model development activities.

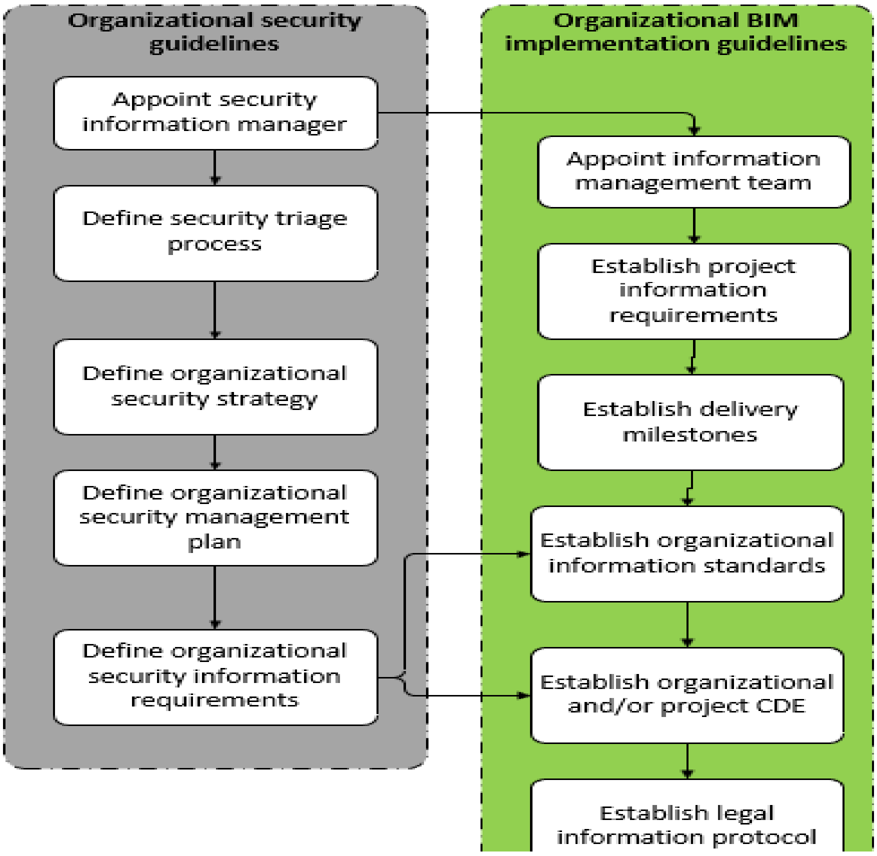


Fig. 3. Relationship between organizational security and organization BIM implementation guidelines

A master process model modelled in BPMN, with all the sequence between all the processes from all three management groups, was developed with all 85 constitutive processes that were created for this framework. Due to its extension, it will not be represented in this work, but Figure 3 shows an extract of the process, which details the relationship and the sequence of model management group activities and their related security guidelines.

In addition, a task chart was still created in order to detail the master process model into lesser activities. Three examples will be given to illustrate how task chart are organized: Figure 4 shows the sequence related to the organizational security measures process, while Figure 5 shows the sequence related to the organizational BIM implementation.

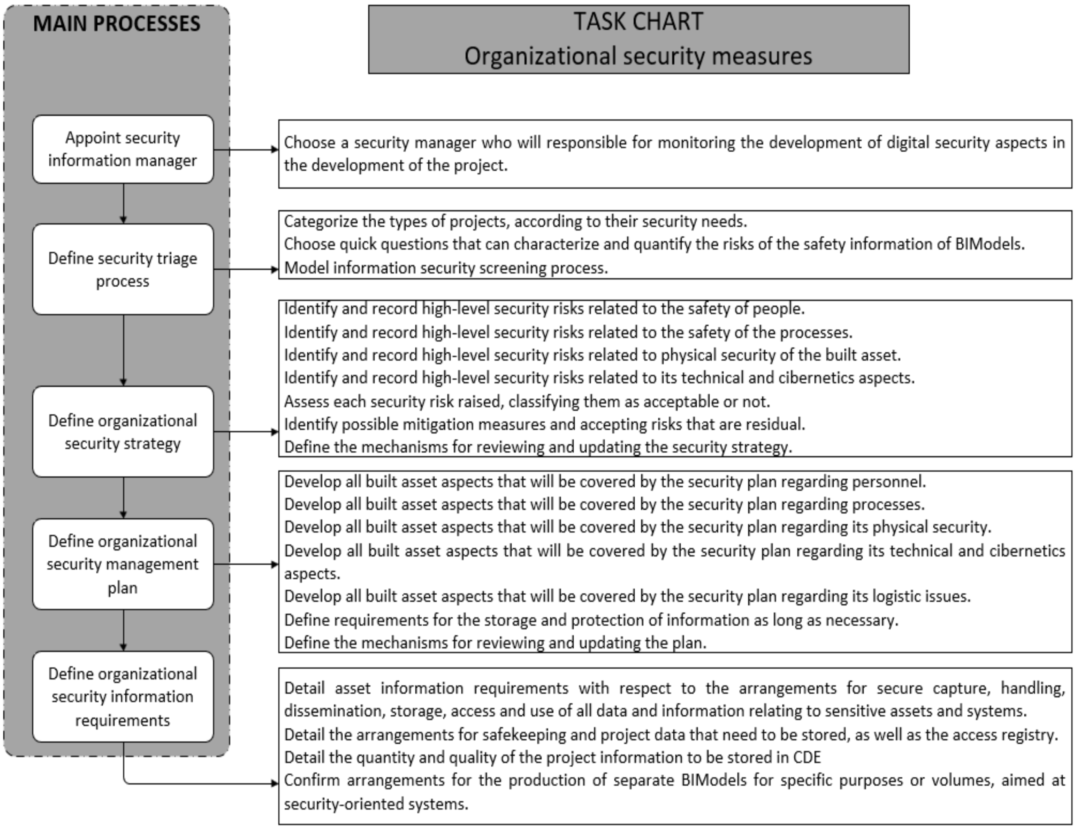


Fig. 4. Process modelling and task chart related to organizational security measures

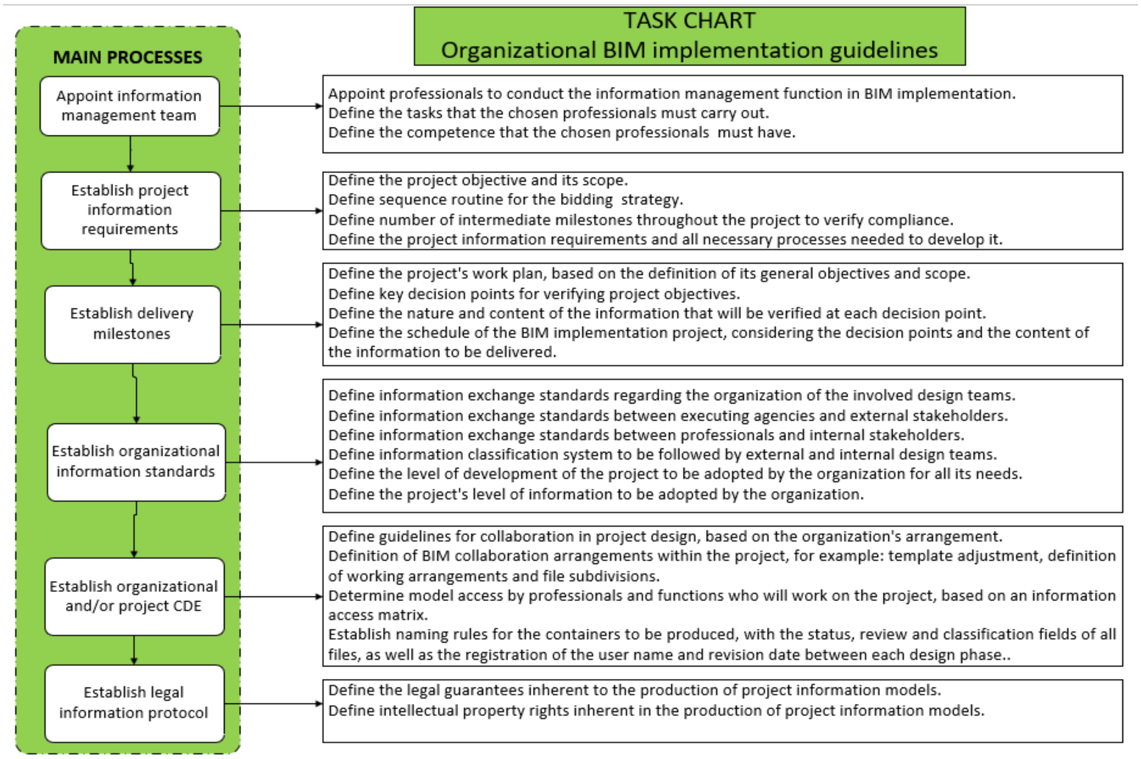


Fig. 5. Process modelling and task chart related to organizational BIM implementation

# 5 ARTIFACT APPLICATION

To evaluate all procedures created, in respect to its applicability to a sensitive environment, an artifact application was developed in an organization which is currently considered one of the references in BIM usage in Brazilian public service.

The experiment took over in a design office specialized in design development, during the second semester of 2018, period when face-to-face interviews and case studies were conducted. All projects are generally destined to the military use, like headquarters and barracks, that always follow a standardization through standard projects or reference projects.

However, this project, which was supervised in this research, has got specific requirements. It will be built in an area of about 20,000 square meters, with a constructed area on a plot of about 28,000 square meters, formed by a building with five floors, being them underground, ground and three floors.

It will have specific security-related rooms and special security installations. Due to project order of magnitude and its sensitive design, a BIM implementation with some special characteristics became mandatory.

## 5.1 Brief project description

Since project initiation, it develops basically as the synergy of two separate projects: the design development itself and the BIM implementation in the project office. BIM implementation in project office aimed to optimize collaborative work within the project process, obtaining all necessary means – personnel, hardware, software and networking solutions - to guarantee its success.

A BIM outsourced consultancy was also contracted, whose mission was the technology transfer as a progressive process of BIM implementation, involving development of a BEP, component library development and all necessary software training and support for adequate design development.

After consultancy contract award, diagnostic meetings between the consultant and office representatives were then held. The deployment sequence developed by the consultancy was based, with due adaptations to the office environment, in the steps defined in the BIM Project Execution Planning Guide, from Pennsylvania State University (PSU, 2011). First case uses to be developed were the design authoring, 3D coordination, cost estimation and phase planning, so that the technical requirements, budget development and schedule planning were directly included from beginning of the design.

A Common Data Environment (CDE) was created within existing organization network, where all professionals had to develop their model designs. The use of any cloud based CDE, as well as any cloud communication platforms, has been banned.

Interoperability between software were then based in proprietary file formats, when software was part of the same suite, and IFC (Industry Foundation Classes). However, in both cases, when any software was not IFC-compatible, even DXF file format was used. All interoperability guidelines were included in the BEP, and all interaction between them as represented in Figure 6, which shows BIM tool ecology and its X axis corresponding to design evolution.

Geometric coordinates are shared from the design beginning, either through work sets or through model links to a federated model. Design model is formed by 26 different models, and generally their creation is based in the design disciplines, the number of the engineers and architects involved, and convenience for information security.

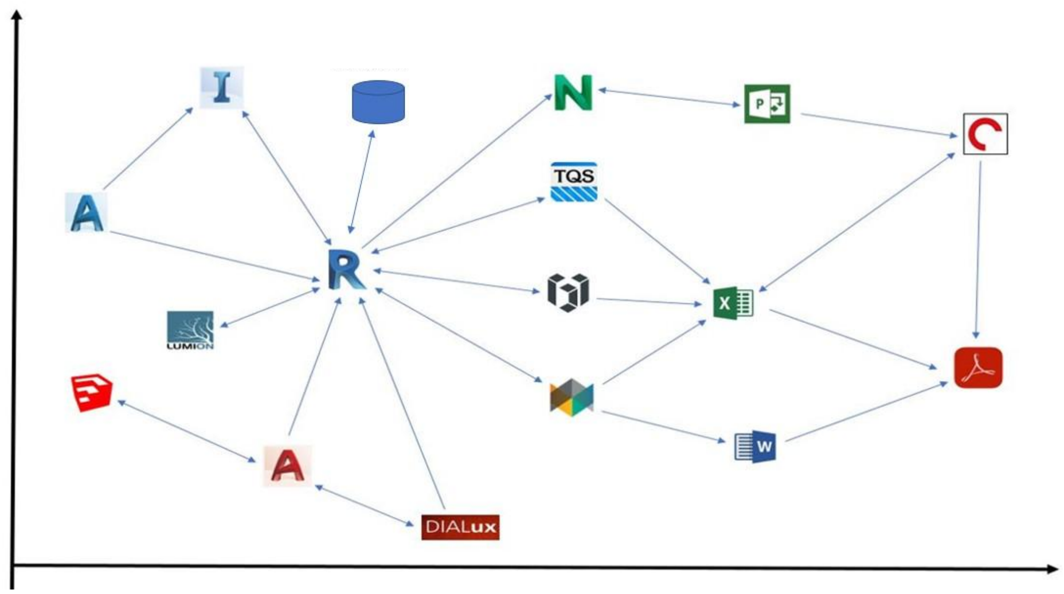


Fig. 6. BIM tool ecology for the office, emphasizing all interactions among software and information

Table 1. BIM and not-BIM software in the BIM tool ecology displayed in Fig 6.

| USE | SOFTWARE | LOGO |
|---|---|---|

| | | |
|---|---|---|
| Drafting | Trimble SketchUp | |
| 2D Drawings | Autodesk AutoCAD 2018 | |
| 3D Models | Autodesk Revit 2018 | |
| Clash Detection and 4D Simulation | Autodesk Navisworks 2018 | |
| Infrastructure Design | Autodesk Civil 3D 2018 | |
| Structural Design | TQS 20 | |
| Structural Design | AltoQI Eberick 2018 | |
| MEP Design | AltoQI QI Builder 2018 | |
| Lighting Simulation | DIALux | |
| Text Editor | Microsoft Word 2017 | |
| Spreadsheet Creation | Microsoft Excel 2017 | |
| Rendering | Lumion | |
| PDF Documents | Adobe Reader | |
| Project Planning | Microsoft Project 2017 | |
| Project Budgeting | Compor90 | |

All design development was developed over several meeting cycles, expanding from design programming to schematic and detailed design using BIM software. Thus, with specific software at their disposal, the collaboration and interoperability procedures made clash detection easier and more efficient.

4D planning efforts were also carried out, following a defined process based in the extraction of the quantity take-offs from all discipline models. 5D planning was also based in these QTO, although there was no direct interface of BIM authoring tools and the budget development software adopted. Although budget process was constantly error-prone, an experienced planner revised project budget and schedule all the time.

Nowadays, detailed design is near completion. The stakeholders seek from federal agencies the money needed to bid and contract the construction.

## 5.2 Artifact evaluation

In this research, the framework will be evaluated in the planning phase of the project, represented with a blue rectangle in Figure 4. Although a total of 45 process were defined in this project phase during this research, only the more representative ones are evaluated in this work.

All process models and task charts, which were created, have had their applicability evaluated. According to its applicability, that is, the way how developed models and task charts could be applied in a sensitive project environment, each process was classified in 4 categories:

- not applicable: no task could not be applicable in the organization design process.
- not relevant: where few tasks could be applicable.
- very relevant: where most tasks could be applicable.
- totally applied: where all tasks could be applicable.

### 5.2.1 Product Management.

These activities were already integrated to day-to-day activities, actually because of the high definition and consolidation of rules for project planning and design development, as showed in Table 2. Since design initiation, they have involved not only design development activities, but all efforts related to design decision-making meetings and availability of all data and information to all stakeholders. All design phases related to the collaborative production of information are still in development, so they are not represented in this research.

Table 2. Evaluation of applicability and relevance of the process created.

| Processes inside PRODUCT MANAGEMENT | | Not applied | Not relevant | Very relevant | Totally applied |
|---|---|---|---|---|---|
| Design planning | Design initiation | | | ■ | |
| | Feasibility analysis | | | ■ | |
| | Data collection | | | | ■ |
| | Programming | | | | ■ |

### 5.2.2 Governance Management.

In general, governance management activities are already well-defined and integrated to design office, as showed in Table 1. Because of the BIM implementation and all effort required for its adequate development, some difficulties were encountered.

The first reason is the innovative characteristic of a public project and its compatibility to rigid governance rules and related bidding acts. The second reason, principally in the consultancy bidding process, is the lack of comprehension of some specific concepts of BIM by bidding and legal managers.

Table 3. Evaluation of applicability and relevance of the process created.

| Processes inside GOVERNANCE MANAGEMENT | | Not applied | Not relevant | Very relevant | Totally applied |
|---|---|---|---|---|---|
| Project initiation | Construction Request Management | | | | ■ |
| | Annual Request Definition | | | | ■ |
| | Organizational rules for project planning | | | | ■ |
| Mobilization | Develop all necessary bidding process | | | | ■ |
| | Manage bidding processes in support of the project | | | | ■ |
| | Manage contractual arrangements | | | | ■ |
| | Manage all personnel for the project development | | | | ■ |

### 5.2.3 Model Management.

Product design was developed alongside with BIM implementation. After project initiation, BIM implementation and execution plans were created. Although these documents had relevance, many of their items could not be applied, partially because of the relationship among the project stakeholders and different understandings between design office and project owners.

BIM execution plan was developed so that all other offices could adopt it to its designs, so local BIM implantation has since its initiation was created in order to become organizational BIM implantation guidelines.

Table 3 shows applicability evaluation of processes, where local guidelines were totally applied, and organizational guidelines are still being studied in order to apply it in other design offices.

Table 4. Evaluation of applicability and relevance of the process created.

| Processes inside MODEL MANAGEMENT | | Not applied | Not relevant | Very relevant | Totally applied |
|---|---|---|---|---|---|
| Organizational BIM implementation guidelines | Appoint information management team | | | ■ | |
| | Establish project information requirements | | | ■ | |
| | Establish delivery milestones | | | ■ | |
| | Establish organizational information standards | | | ■ | |
| | Establish organizational and/or project CDE | | | ■ | |
| | Establish legal information protocol | | | ■ | |
| | Survey current infrastructure conditions | | | | ■ |
| Local BIM implementation guidelines | Appoint local BIM manager/information management team | | | | ■ |
| | Define BIM local implementation plan | | | | ■ |
| | Define BIM Execution Plan | | | | ■ |
| | Define interoperability standards | | | ■ | |

### 5.2.4 Security Measures in BIModels

There were several difficulties for any official adoption of security measures, as can be seen in Table 4. Most processes related to information security were applied only with respect to security breach information plans and personnel hiring policy, and they are already part of previous existing plans. In relation to BIModels, there were few contributions of security requirements to BIM implementation and execution plans. Design professionals received only basic security orientations and BIM consultants had little knowledge about the sensitive aspects of the project.

Table 5. Evaluation of applicability and relevance of the process created.

| Processes inside SECURITY ISSUES IN BIModels | | Not applied | Not relevant | Very relevant | Totally applied |
|---|---|---|---|---|---|
| Organizational directives | Appoint security information manager | ■ | | | |
| | Define security triage process | ■ | | | |
| | Define security strategy | | ■ | | |
| | Define security management plan | | ■ | | |
| | Define security information requirements | ■ | | | |
| Local directives | Appoint security information responsible | | ■ | | |
| | Define security management plan | | ■ | | |

| | |
|---|---|
| Define security information requirements | |

## 6 CONCLUSIONS

The aim of this article was to develop processes which would contain all the main factors that guarantee an optimized development of a construction project with the use of BIM, also considering its sensitive aspects related to security-minded BIM.

The process were divided into three groups: model management, directly related to BIM implementation, with BIM execution plan and BIModel development; product management, directly related to design and to project at all their stages of development, and governance management, related by the demand for construction, project planning, and the development and execution of bidding documents and hiring processes.

From what is seen in this research, one can consider that the three groups constitute parts of a tri-axial conceptual structure where each one has a broad relationship with each other. In general, a BIM implementation usually occurs with the synergy of two projects: the BIM implementation itself in the organization that conducts and discipline the management of model information, and the development of a pilot project.

The guarantee of the success of any implantation in public environment is to manage both projects and make them compatible with public governance processes: hiring staff, purchasing means such as hardware, software, network solutions and specific training; mandatory legal analysis of all public management proceedings and finally, how all these activities are managed by the public organization. It was seen that most of these processes are not still known by the professionals not directly involved to the design: managers, owners, attorneys.

In view of the processes modeled and all their application to the office, most of them have been fully applied. Particularly product management processes benefited from the arrival of new technologies and collaborative information production processes.

BIM implementation processes, on the other hand, must necessarily consider the characteristics of the organization in which they are employed. In the specific case of this evaluation, the definition of organizational and internal guidelines was applied, albeit some tasks were not totally applied in organization.

In general, security issues in BIModels are very unfamiliar to design professionals, and its relationship with other processes groups is still unknown. All plans related to sensitive design must be developed prior to its initiation, and a specific security manager must be appointed by the organization.

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# SEMANTIC WEB FOR INFORMATION EXCHANGE BETWEEN THE BUILDING AND MANUFACTURING INDUSTRIES: A LITERATURE REVIEW

**Rehel Kebede[1], Annika Moscati[2], and Peter Johansson[3]**

**Abstract:** Easy and solid information exchange constitutes an important part in BIM-based projects. To conduct reliable simulations and optimizations, information about products, such as luminaries, windows, doors, etc., need to be provided by the manufacturing industries to the building designers at the early design stage. Several studies and ongoing researches presented the Semantic Web (SW) and Linked Data (LD) technologies as an interoperable and flexible approach for providing product information from the manufacturers during the design and construction stage as well as gathering consumers data to the manufacturers during the operation stage. A systematic literature review has been conducted to investigate benefits and limitations of using the SW and LD technologies for developing product data templates for information exchanges between the building and product manufacturing industries in comparison with the conventional approach of information ex-changes using the openBIM standards. Results show that SW and LD could apport considerable benefits to the information exchange in the building sector. Moreover, SW and LD technologies enable the sharing of products' in-formation from manufacturers to designers who can search product information, compare different products and take informed design decisions during the very beginning of the design process.

**Keywords:** Product Data Template, Semantic Web, Information Exchange.

## 1 INTRODUCTION

The increasing digitalization in the construction and facility management industry has led to a growing use of virtual computer models and is the prerequisite for data, sensor and simulation driven product development where features of the complex products can be simulated and evaluated. However, this development creates challenges and opportunities for industries delivering products used in construction. The construction industry is the largest single sector in most countries and an important trading partner for the manufacturing industry. Its highly complex products are to a large degree an aggregation of products realized by the manufacturing industry. The growing use of virtual computer models in the different stages of the products' life cycle will put new demands on the information linked to products delivered by the manufacturing industry. In the design stage for example, techniques like parametric design, optimization and multi-criteria decision-making allow the evaluation of thousands of alternative solutions for a built environment (Jalilzadehazhari et al., 2019b, Jalilzadehazhari et al., 2019a). One of the out-comes from this development is that a huge number of products could be

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evaluated in the design phase and from such, the final choice of product could be done. For this to be practically usable though, the information about products need to be automatically retrieved (Jalilzadehazhari et al., 2017, Negendahl, 2015).

In this context, the issue concerns not only the information content, but primarily its storage, querying and reasoning. The research developments in this area focus on the possibility to retrieve information using databases or web links instead of traditional file exchange or centralized file model repositories (Pauwels et al., 2017), the need for flexible systems that enable an easier information updated (Cavka et al., 2017, Zhang et al., 2015) and the requirements for new standards (Zhang et al., 2015, Eastman et al., 2011).

Several initiatives to define and structure product properties are active at present, e.g. the work in CEN/TC 169/WG 1 concerning BIM Properties for Lighting  Luminaires and Sensors. In some of these efforts it has been stated that the base for defining product properties should be the different standards (CEN, ASTM, AU, ISO etc) used to evaluate these properties. It has also been shown that there is a big gap be-tween how products are described by designers in the building industry as well as designers in the manufacturing industry. To overcome this gap, efforts are made to standardize (Product) Data Templates (DT) for different categories of products. Most of these works are based on the so called "PPBIM" (prEN ISO 23386/23387) which describes a methodology and the framework for properties and Data Templates. One of the main tools in the methodology are dictionaries. The dictionaries should contain the definitions of the attributes describing a property of a product and give each attribute a GUID. The buildingSMART Data Dictionary (bsDD) is one example of such a Dictionary, and probably the most referred one. It has also been stated that bsDD should contain and uniquely define the DTs, by giving each DT a GUID.

Despite standardization efforts, there is no globally agreed product data standard available by which product data can be created and provided by the manufacturers digitally (UKBIM, 2018).

Completed and ongoing studies suggest Semantic Web (SW) and Linked Data (LD) as technologies that allow a more interoperable and flexible approach for providing product information from the manufacturers during the design and construction stage as well as gathering consumers data to the manufacturers during the operation stage.

Therefore, a systematic literature review has been conducted in order to investigate the benefits and limitations of using the SW and LD technologies for developing product data templates for information exchanges between the building and lighting product manufacturing industries in comparison with the conventional approach of information exchanges using the openBIM standards.

The research question has been formulated using the PICOC framework further described in the "research method" section, together with the whole search strategy. From a total of 519 papers retrieved, following an analytical inclusion / exclusion criterion described in section 2.2, a total of 26 papers have been identified as relevant for the study's scope. Among them, one paper has been chosen as index paper against which concepts extracted from other retrieved papers are compared with and categorized accordingly while reporting the findings of this review.

The results will be presented as follows:

- Benefits of the Semantic Web and Linked Data Technologies, further categorized into
- ontology-based information management and sharing,

- combine product manufacturer data with building data and
- support building performance analysis and optimization.
- Limitations of the Semantic Web and Linked Data Technologies
- Limitations of Existing BIM Technologies.

The literature review results show that many are the benefits that an extensive use of SW and LD could apport to the building sector. However, limitations will be presented and discussed, as well as suggestions for further researches. It is also important to state that this paper is part of a large research project titled Manufactured products' information provision for light environments (MAP4Light), co-funded by the Swedish Knowledge foundation (KK) together with four industrial partners. MAP4Light aims to study and develop new digital tools for product information exchange between the manufacturing and building industries focusing on products in light environments. Therefore, these two latter concepts (lighting products and environments) were included in the literature review strategy. However, the lack of papers facing these specific topics led to a more generic analysis and to the need of further studies to satisfy MAP4Light's needs.

# 2 Research method

## 2.1 Identifying Relevant Studies

The systematic search process of this review follows the methodology described by Booth et al. (2016). A framework called PICOC has been used to formulate the re-search question. The acronym PICOC stands for Population and their problem, Intervention or Issue, Comparative Intervention, Outcomes or themes and Context (Booth et al., 2016). Accordingly, both the scope of the research and the different parts of the research question are identified using this framework as shown in Table 1. Formulating the research question in this manner facilitates identification of the important keywords through the process of translating the research question into its relevant search concepts.

The main source of information chosen for this study was the Scopus database because Scopus is a multi-disciplinary database with easy features to refine the search results by year, document types, authors and affiliations. It is the largest abstract and citation database of peer-reviewed papers with relatively large coverage in comparison with other databases such as Web of Science and Google Scholar (Mongeon and Paul-Hus, 2015, Leslie, 2013, Burnham, 2006).

As indicated in Table 1, the scope of the review is identified, and the following research question is formulated: 'What are the benefits and limitations of using the SW and LD technologies for developing product data templates for information ex-changes between the building and lighting product manufacturing industries in comparison with the conventional approach of information exchanges using the openBIM standards?'

Subsequently, the search concepts are extracted from the research question and the relevant synonyms are identified for each search concept as shown in Table 2.

Table 1: Research question formulation using the PICOC framework

| | |
|---|---|
| P<br>Population and their problem | Population:<br>• lighting product manufacturers<br>• building lighting engineers<br>Problems:<br>• Information exchange |
| I<br>Intervention and issue | Intervention<br>• The Semantic Web and Linked Data technology<br>Issue:<br>• Limitations of these technologies |
| C<br>Comparative Intervention | • The conventional approach of information exchanges using the openBIM standards |
| O<br>Outcomes or themes | • An improvement in information exchanges (improved interoperability) |
| C<br>Context | • Building and lighting product manufacturing industries |

Table 2: Search concepts and Synonyms

| Search concepts | Synonyms |
|---|---|
| Product data template (c1) | ("building catalog*" OR "building component*" OR "building product*" OR "object type librar*" OR "online product library" OR "product catalog*" OR "product component" OR "product data" OR "product manufacturer data" OR "product sheet" OR "product template") |
| Semantic web and linked data technologies (c2) | ("linked data approach*" OR "linked data" OR "linked datum" OR "resource description framework" OR "semantic description*" OR "semantic technolog*" OR "semantic web" OR "web ontolog*" OR ontolog* OR "application of ontolog*") |
| Building industries<br>Manufacturing industries (c3) | ("AEC*" OR "AEC project*" OR "building industr*" OR "construction industr*" OR "manufactur* industr*" OR building* OR construction OR manufacturer* OR "lighting component* manufactur*") |
| openBIM standards (c4) | ("IDM-MVD standards" OR "MVD and IDM approach*" OR "Model View Definition" OR mvdXML OR "Industry Foundation Class*" OR "buildingSMART Data Dictionary") |
| Information exchange (c5) | ("information exchange*" OR "exchange of information" OR "information requirement*" OR interoperability OR "information model*" OR "Information technolog*" OR "Information management" OR "data management" OR "data exchange") |
| BIM (c6) | (BIM OR "Building information model*" OR "Building information management" OR "BIM service" OR "BIM technolog*") |
| lighting product manufacturing industries (c7) | (lighting OR "lighting product manufacturer") |

The search strategy, which is the search concepts combined with Boolean Operators, is used to locate the relevant papers. The search strategy, search result, search field and search date are given in Table 3. The most important search concepts have been used in all search combinations as a common denominator to ensure retrieval of the relevant papers.

Table 3: Search strategy, search result, search field and search date

| Search strategy | Search result /No of hits | Search field | Search date |
|---|---|---|---|
| c1 AND c2 | 348 | title-abs-key | Nov 24, 2019 |
| c1 AND c2 AND c3 | 117 | title-abs-key | Nov 24, 2019 |
| c1 AND c2 AND c3 AND c4 | 5 | title-abs-key | Nov 24, 2019 |
| c1 AND c2 AND c3 AND c4 AND c5 | 5 | title-abs-key | Nov 24, 2019 |
| c1 AND c2 AND c3 AND c6 | 30 | title-abs-key | Nov 24, 2019 |
| c1 AND c2 AND c5 AND c7 | 13 | all fields | Nov 24, 2019 |

## 2.2 Paper Selection Process

A total of 519 papers were identified with the presented search strategy. Given the small number of hits, search limitation by year was not applied. All the papers were exported to 'Rayyan systematic review web application' for further paper inclusion and exclusion analysis. The following inclusion and exclusion criteria were stated during paper selection process.

Inclusion criteria:

- Papers that discuss the concepts in the research question with the aim of better information exchange using the SW and LD are to be included

Exclusion criteria:

- Papers that discuss the concepts in the research questions with a different context and aim than better information exchange will be excluded.

The paper selection process was started with removing duplicates in the first stage. The duplicates were excluded leaving 372 documents for further investigation. Second, the remaining papers were screened for inclusion by examining the titles. In total, 71 papers are left for further analysis of inclusion by reading the abstract. Finally, 25 studies were included for full-text analysis based on the stated inclusion and exclusion criteria, out of which 19 studies are included for qualitative synthesis. Additional 7 studies were added using the snowballing literature-searching technique. A total of 26 studies were included for the review and is presented in Table 4. The diagrammatic representation of the paper selection process is shown in Figure 1 with PRISMA flow diagram.

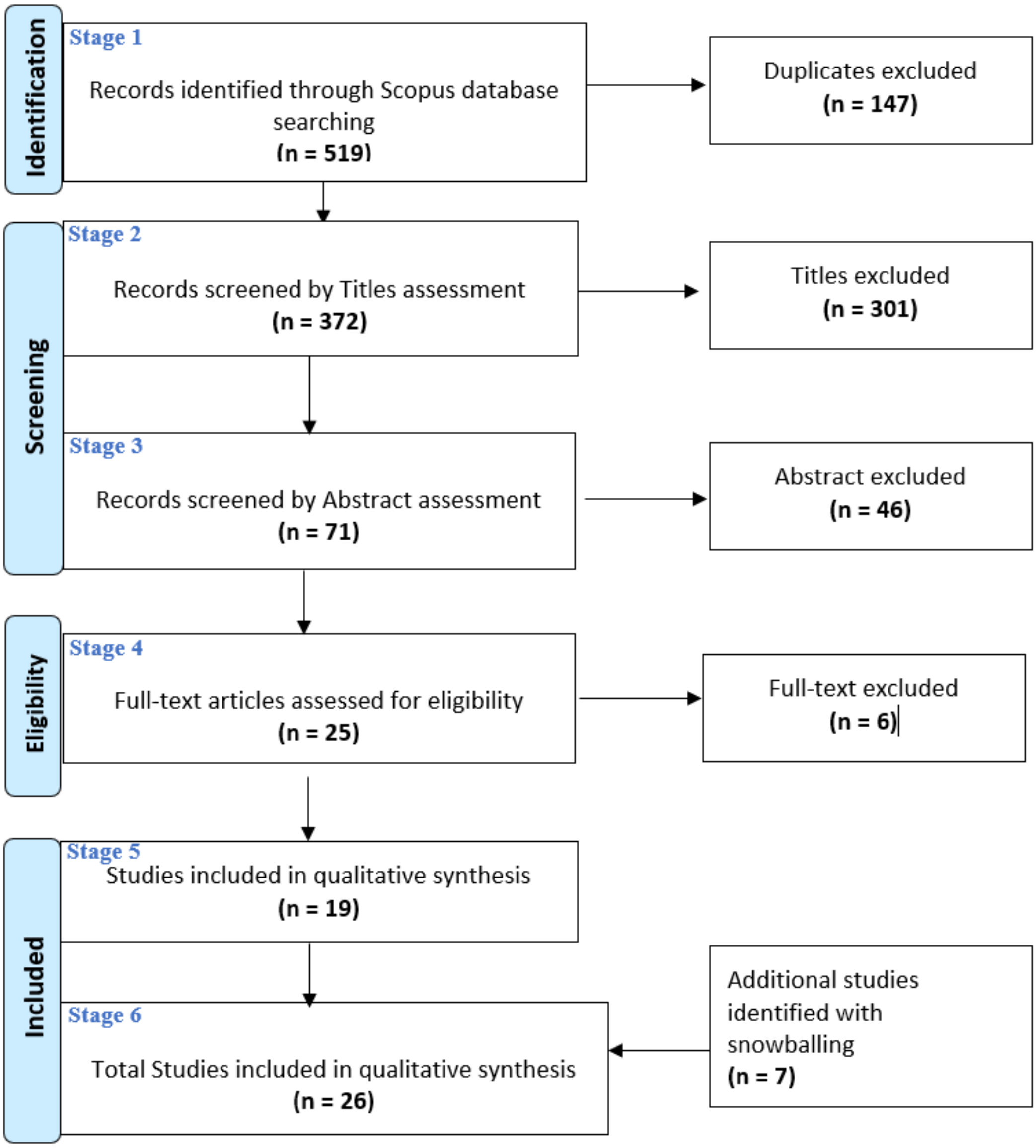


Figure 1: Paper Selection Process (PRISMA flow diagram)

Table 4 Articles Included in the Literature Review

| No | Authors | Title |
|---|---|---|
| 1 | Abdul-Ghafour et al. (2014) | Semantic interoperability of knowledge in feature-based CAD models |
| 2 | Bassier et al. (2019) | Towards the Semantic Enrichment of Existing Online 3D Building Geometry to Publish Linked Building Data |
| 3 | Bauer et al. (2019) | Towards Semantic Interoperability Standards based on Ontologies |
| 4 | Berlo et al. (2019) | Creating Information Delivery Specifications using Linked Data |
| 5 | Bilal et al. (2017) | The application of web of data technologies in building materials |

| No | Authors | Title |
|---|---|---|
| | | information modelling for construction waste analytics |
| 6 | Bonduel et al. (2018) | The IFC to linked building data converter - Current status |
| 7 | Corry et al. (2015) | A performance assessment ontology for the environmental and energy management of buildings |
| 8 | Costa et al. (2015) | Connecting building component catalogues with BIM models using semantic technologies: An application for precast concrete components |
| 9 | Costa (2017) | Integration of building product data with BIM modelling: a semantic-based product catalogue and rule checking system |
| 10 | Felic et al. (2014) | Process-oriented semantic knowledge management in Product Lifecycle Management |
| 11 | Gao et al. (2014) | BIMTag: Semantic annotation of web BIM product resources based on IFC ontology |
| 12 | Godager (2018) | Critical review of the integration of BIM to semantic web technology |
| 13 | Gudnason and Pauwels (2016) | SemCat: Publishing and accessing building product information as linked data |
| 14 | Huang et al. (2019) | Data-driven ontology generation and evolution towards intelligent service in manufacturing systems |
| 15 | Krima et al. (2012) | Dynamic customization and validation of product data models using semantic web tools |
| 16 | Lou (2011) | A method toward building semantic-enriched product model |
| 17 | Lu et al. (2015) | Enriching the semantics of variational geometric constraint data with ontology |
| 18 | Moreno et al. (2011) | Application of Product Data Technology Standards to LCA Data |
| 19 | Niknam et al. (2019) | Integrating BIM and product manufacturer data using the Semantic web technologies |
| 20 | Niknam et al. (2017) | A shared ontology approach to semantic representation of BIM data |
| 21 | Pauwels et al. (2017) | Semantic web technologies in AEC industry: A literature overview. Automation in Construction |
| 22 | Pauwels et al. (2016) | EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology |
| 23 | Pauwels et al. (2015) | Linked Data in Architecture and Construction |
| 24 | Scherer et al. (2011) | A distributed multi-model-based Management Information System for simulation and decision-making on construction projects |
| 25 | Shayeganfar et al. (2013) | An ontology-aided optimization |

| No | Authors | Title |
|---|---|---|
| | | approach to eco-efficient building design |
| 26 | Wagner and Ruppel (2019) | BPO: The Building Product Ontology for Assembled Products |

# 3 Results

## 3.1 Descriptive Analysis

The identified papers are classified by year to see the distribution of them across the years. Figure 2 shows that 23.08 % of the retrieved paper is published in the year 2019 taking the lead. The next higher number of papers are published in 2015 and 2017 each with percentage of 15.38%. This figure displays the research community's growing interest in the analysed subject.

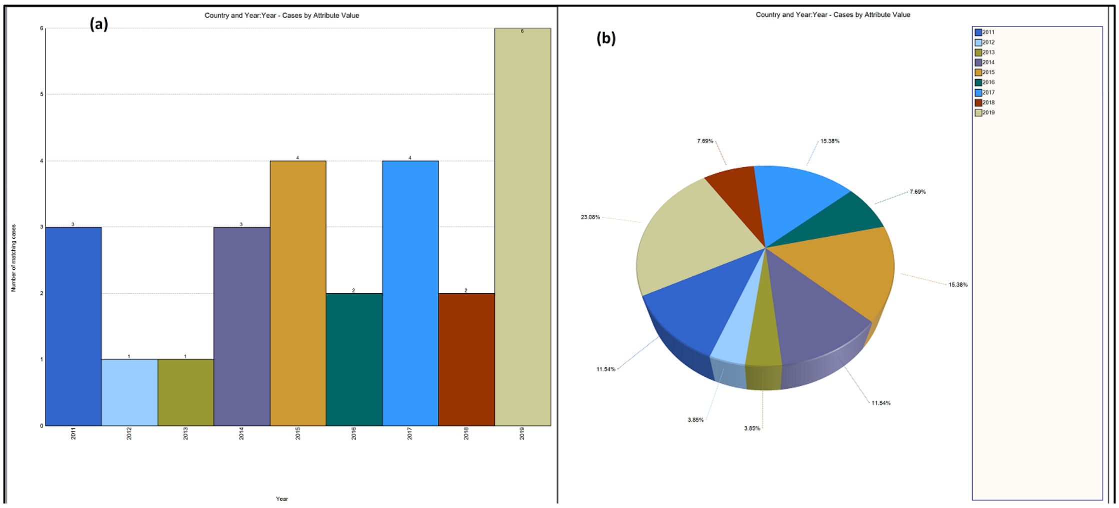


Figure 2 Number of Publications Retrieved for the Review (a) by year (b) in percentage

Booth et al. (2016) characterized three types of data synthesis in a systematic literature reviews namely aggregative, configurative and integrative. This research followed the aggregative data synthesis approach as the intention of the research was to bring multiple studies together and examine concepts or ideas that are relevant to answer the research question.

The identified papers are exported to NVivo 12 for data extraction and subsequent qualitative data analysis. The data extraction was guided by the review's research question while identifying and coding the relevant information in NVivo.

Booth et al. (2016) suggest to starting the qualitative analysis of the review by reading through the retrieved papers with subsequent selecting of an index paper. They defined index paper as a paper selected from the retrieved papers based on its conceptual richness, number of citations, age etc., for the purpose of comparing all papers against the chosen index paper. In addition, the selection of the index paper is influenced by the purpose of the review. Because of its conceptual richness and relative high number of citations, the paper Pauwels et al. (2017) was chosen as an index paper against which concepts extracted from other retrieved papers are compared with and categorized accordingly while reporting the findings of the review. Pauwels et al. (2017) conducted an extensive literature overview related to the development and application progress of semantic web technologies in the AEC domains. They have outlined three application areas of the semantic web as shown in Table 5, namely: interoperability, linking across domains and logical inference and proofs.

This review specifically emphasizes the area of product information exchange between the building and product manufacturers which Pauwels et al. (2017) categorizes this area under "linking across domains" application area. Based on the scope of the review, the first three use cases mentioned under the category "Linking across domains" (see Table 5) were chosen as a model or framework through which the benefits are extracted and categorized. The use cases are:

- ontology-based information management and sharing,
- combine product manufacturer data with building data and
- support building performance analysis and optimization.

It is worth mentioning that all application areas are not mutually exclusive.

## 3.2 Result

### 3.2.1 Benefits of the Semantic Web and Linked Data Technologies

Ontology-based information management and sharing: Ontologies serve as a medium to represent and model information using ontology languages such as the Resource Description Framework Schema (RDFS) and Web Ontology Language (OWL). These technologies offer an opportunity to model and combine heterogenous information from diverse knowledge domains (Pauwels et al., 2017). Gudnason and Pauwels (2016) mentioned how building product information are heterogeneous, unstructured and produced in incompatible semantics in the building industry. It is a current trend that manufacturers provide their product information mostly in PDF format (Niknam et al., 2019, Costa and Madrazo, 2015, Berlo et al., 2019). Consequently, building designers are obliged to manually insert this information into their BIM tools, which is usually error-prone and inefficient (Niknam et al., 2019). Hence, there is a need for an integration of product data using ontology where data is structured and connected on the web so that it can be processed by machines (Niknam and Karshenas, 2017).

Table 5 Use cases of semantic web technologies in the AEC industries (Pauwels et al., 2017)

| Interoperability | Linking across domains | Logical inference and proofs |
|---|---|---|
| Enable vendor-neutral model exchange | Ontology-based information management and sharing | Check model consistency and completeness |
| Combine different information representations | Combine product manufacturer data with building data | Enable automated regulation compliance checking |
| Support use case-based information exchange | Support building performance analysis and optimization | Logical inference use cases including building energy performance, construction safety, cost estimation, home automation and etc. |

| | |
|---|---|
| | Connect BIM and GIS |
| | Enable automated regulation compliance checking |

Several studies suggested an ontology-based information management method to unify and integrate heterogeneous data from diverse data sources (Pauwels et al., 2017, Gudnason and Pauwels, 2016, Costa and Madrazo, 2015, Huang et al., 2019). In this regard, ontologies offer the possibility "to collect and combine data from multiple heterogeneous sources and provide a homogeneous view of information thereby making the information accessible and useable to the end users and applications" (Costa and Madrazo, 2015). Ontology-based product data management is also acknowledged and embraced in the technical roadmap of the buildingSMART as showed in Figure 3. The most popular three BIM adoption levels are extending to the next level to incorporate the application of semantic technologies in product data management on the basis of ontology (Pauwels et al., 2017, Godager, 2018). This calls for attention and preparation for all domains involved in the AEC industry, including the manufacturers.

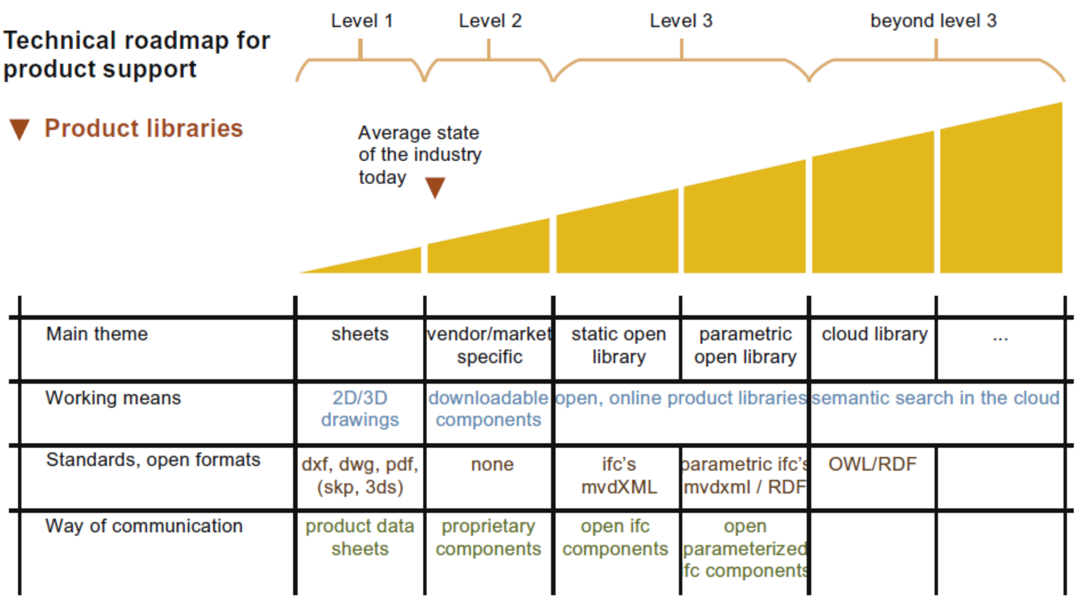


Figure 3 The technical roadmap for product support (Pauwels et al., 2017)

Numerous studies collected for this review adopted the definition of an ontology as a ‘formal, explicit specification of a shared conceptualization’, that provides a shared vocabulary that can be used to model semantic information effectivity (Niknam et al., 2019, Costa and Madrazo, 2015, Moreno et al., 2011, Lu et al., 2015, Costa Jutglar, 2017). Thus, ontologies have the potential to enrich the semantics of product geometry as well as express the semantics of product data unambiguously. With the use of ontology, it has become possible to easily describe the real-world products in a homogeneous machine-processable format (Shayeganfar et al., 2013, Abdul-Ghafour et al., 2014, Bassier et al., 2019, Wagner and Rüppel, 2019). Modelling and representing knowledge in this manner facilitates an automated searching and using of building product data at the early design stage thereby enabling designers to optimize their design decisions (Shayeganfar et al., 2013).

Furthermore, ontologies are useful to represent knowledge formally and create a shared knowledge base, from which knowledge can be inferred automatically which allows manufacturers develop an idea or concept for their new products (Felic et al., 2014). Once ontology is developed, an added benefit such as reasoning to infer logical conclusion, consistency checking and semantic queries can be performed. This enables data integration, creation of new knowledge from the existing data and execution of sophisticated data query in multiple domains (Pauwels et al., 2017, Godager, 2018, Lu et al., 2015, Krima et al., 2012).

Combine product manufacturer data with building data: One of the envisaged benefits by adopting the SW technologies in the building industry includes the ability to link building information models with the product manufacturer's data (Godager, 2018, Pauwels et al., 2015). Manufacturer's product descriptions required to conduct building performance analysis can be readily accessible, usable and searchable on the web with the unifying language of semantic web and linked data (Pauwels et al., 2017). Data stemming from both the building and manufacturing domain can be described and linked homogeneously in RDF, using the RDF triples subject-predicate-object (Corry et al., 2015). This opens an opportunity for designers to explore possible design alternatives to optimize building performances. On the other hand, it increases collaboration of the involved actors through a com-mon platform and encourages the engagement of building product manufacturers during the design stage (Pauwels et al., 2017, Costa and Madrazo, 2015, Shayeganfar et al., 2013).

Manufacturers have been using standard product data templates, such as Specifier's Properties information exchange (SPie), and catalogues of BIM objects, such as BIMobject, to deliver BIM data. Such templates model and exchange information based on open industry standards (Gudnason and Pauwels, 2016). Gudnason and Pauwels (2016) mentioned that the application of such templates has been improving and have added value within the construction supply chain. However, the marketing business models of the manufacturers supply chain has not been improved for several years (ibid). As a result, "information providers collect product information in web portals from manufacturers, usually for a fee, to allow designers to search, analyse, compare and reuse the information" (ibid). The application of the semantic web and linked data prove to be suitable to support the manufacturers' supply chain for representing the engineering properties of product design as well as managing product information by: "linking product data with other data sets, creating customized data sets for specific stakeholders and providing suppliers with detailed and structured product data"(ibid).

Currently, one of the major problems in the building performance optimization process include lack of mechanisms for comparing products of the same type sup-plied by different manufacturers (Moreno et al., 2011). To carry out a legitimate comparison of products, real and timely information about the product and processes as well as information about the precise inputs into those products and processes is required (Moreno et al., 2011, Shayeganfar et al., 2013). A good example would be comparison of products from the environmental point of view which can be achieved with LCA (Moreno et al., 2011). It is well known that LCA requires the gathering of real data throughout the life cycle of the product. Therefore, "it is necessary to know what resources have been consumed and what waste has been emitted to the environment in the making of each part within an assembly of the product" (ibid). In this regard, the semantic web enables product manufacturers to browse the supply chain and gather information about each component of the product. All products, product components, and activities can be represented as a resource in RDF and uniquely identified by uniform resource identifier (URI) (ibid). The URI can then be imprinted on the product to make the information about the product available whenever is needed (ibid). It should be mentioned that, while the URI always represents the same product in both human and computer readable for-mat, there is also a need to maintain the data on the web throughout the lifecycle of the product. This helps to facilitate maintenance as well as provides information on the final disposal of products (ibid).

Another benefit empowered by the semantic web technology is the ability to publish concept libraries in both top down and bottom up approach (Pauwels et al., 2017, Berlo et al., 2019). The top down approach necessitates the need for international product classification standard within large concept libraries. The bsDD is an example of top down approach which enables end users explicitly identify convenient products for their specific cases (Pauwels et al., 2017, Berlo et al., 2019). On the other hand, the bottom up approach offers end users the ability to create and manage new concept libraries in distributed manner as opposed to the centralized data management that relies on common data standards (Berlo et al., 2019, Godager, 2018). This would in turn make extensibility easier and provide designers the flexibility they need to realize various design scenarios instead of being limited to the predetermined design alternatives as it is with top down approach (Berlo et al., 2019, Niknam and Karshenas, 2017). As it is mentioned by Pauwels et al. (2017), a bottom up approach encourages to 'try to interpret, accommodate and model what is, rather than trying to change reality to fit a single model'.

Support building performance analysis and optimization: Shayeganfar et al. (2013) indicates the gap between real world product description and the way they are abstracted in BIM tools. This gap created discrepancy between the real performance of a building and the simulated performance of a building model (Corry et al., 2015). Shayeganfar et al. (2013) continues to explain the potential of the semantic web technologies to bridge this gap given the fulfilment of two prominent components. First, an ontology that describe the real product needs to be created. This includes developing ontologies for different domains required for performance simulations such as construction product standards and regulations, product specification including product cost information, climate data etc.  Second, these product descriptions need to be linked with the building performance assessment and optimization environment to enable investigation of the available design alternatives.

### 3.2.2 Limitations of the Semantic Web and Linked Data Technologies

The primary challenge of the building industry has been the lack of standard BIM-related shared knowledge base (ontology). As a result, the semantic of terms and concepts are incompatible between different applications often resulting in misinterpretation of concepts and loss of information during information exchanges (Lou, 2011, Gao et al., 2014).

To address this challenge, several research efforts have been made to represent the BIM-IFC data with a semantic format by first converting the IFC schema into an OWL ontology known as ifcOWL as general-ontology (Godager, 2018, Scherer and Schapke, 2011, Pauwels and Terkaj, 2016, Bonduel et al., 2018). The ifcOWL is equivalent to the present large and complex IFC EXPRESS schema. Currently the ifcOWL has reached the point where the use of it is encouraged while there still remains issues to address particularly regarding whether or not to convert IFC geo-metric data that requires little semantic meaning (Pauwels et al., 2017). Furthermore, the developed ifcOWL, as equivalent to the IFC EXPRESS schema, is still large and complex which negatively affected the searchability of information (Bonduel et al., 2018).

Other research initiatives in this area include generating an ontology for a specific instance models as domain-ontology rather than directly converting the IFC format to OWL (Pauwels and Terkaj, 2016). This allows individual manufacturers develop their own ontology to capture their specific product data. This approach, however, makes the information isolated and difficult to find for reusing for others outside of the scope (Gudnason and Pauwels, 2016).

Furthermore, the creation and maintenance of links between different datasets has been reported as a challenge in the application of these technologies (Huang et al., 2019, Godager, 2018). The practical implication of this in building industry would be the challenge of maintaining the Linked Building Data (LBD) of products linked and combined with their environmental assessment as RDF statements. RDF statements describing products from real world are open to amendment whenever there is change. In such cases, the RDF triples can be inserted or eliminated to keep the repositories updated. This inevitably affect other links, could cause link breakage or links disappear with no notification (Regino et al., n.d.). It was also noted that ontologies are usually created manually by domain specific experts and ontology experts, which is time consuming and inefficient (Huang et al., 2019, Bauer et al., 2019). In both scenarios mentioned above, full automatic link maintenance and ontology generation has been a research problem in the application of the SW and LD technologies (Huang et al., 2019, Regino et al., n.d.).

The application of the semantic web also put demands on the manufacturers to create product data ontology for their products and make their product data available and transferrable as well as shared and reused (Niknam et al., 2019). This eventually imposes two challenges for the manufacturers. First, manufacturers are not motivated to share their detailed product information openly with the intention of maintaining their competitive market share and distinguishing their product characteristics among their rivals. Second, most building product manufacturers are medium and small size companies with limited economy and adopting the semantic web technology would mean significant investment in complying with industry product specification (Gudnason and Pauwels, 2016).

### 3.2.3 Limitations of Existing BIM Technologies

Currently, the EXPRESS-based IFC schema is widely used as an open exchange standard for representing building information in neutral format. IFC is able to successfully exchange information associated with product geometry (Abdul-Ghafour et al., 2014). However, several studies show how the explicit semantics of product data cannot be represented and automatically exchanged by existing standards (Godager, 2018, Moreno et al., 2011, Lu et al., 2015). There are possible ways to extend the IFC definitions, to include the semantics of products, using IfcProxyElement, Property sets and referring to elements in bsDD and external object type library (Berlo et al., 2019). However, the IFC schema requires strong familiarity with the EXPRESS language to take advantage of its extensibility and it has not been possible to extend the IFC schema on-the-fly in a user-friendly way (Pauwels et al., 2017, Bonduel et al., 2018).

Bilal et al. (2017) and Gao et al. (2014) also added the data of building design can be captured by the IFC schema while the data of building products, such as cost, alternative products, product functions, dimensions, materials, performance, attainability, manufacturers etc., are not yet embedded in the product and are provided by the manufacturers as an associate document to BIM models. Besides, consistency checking, reasoning and semantic queries are difficult to apply on the IFC building models (Lu et al., 2015). In general, as it is explained by Godager (2018), the semantic web ontology-based approach significantly diminishes the major challenges of the current standards.

Thus, SW and LD benefits can be summarized as follows:

- Ontology-based information management and sharing can:
- enable the sharing of heterogeneous information;
- achieve a shared vocabulary;
- create a more stable development of repositories concepts dictionary and concept library;
- represent the real-world products in a homogeneous machine-processable format;
- facilitate an automated searching and using of building product data at the early design stage thereby enabling designers to optimize their design decisions;
- enable data integration, creation of new knowledge from the existing data and execution of sophisticated data query in multiple domains;
- LD and SW technology seem to support reasoning and search in a better manner than most other alternatives.

Through Combine product manufacturer data with building data, it is possible to:

- link building information models with the product manufacturer's data;
- access, use and search on the web manufacturer's product descriptions re-quired to conduct building performance analysis;
- homogeneously describe and link data stemming (from both the building and manufacturing domain) in RDF;
- support the manufacturers supply chain for representing the engineering properties of product design as well as managing product information;
- capture real and up-to-date information about the product using product ontology;
- publish concept libraries in both top down and bottom up approach.
- facilitate the bottom-up approach which would give the producers the opportunity to describe their products using different properties and let de-signers to search for products with other properties than the ordinary ones.

Support building performance analysis and optimization allows to

- bridge the gap between real world product description and how they are abstracted in BIM tools.

From the conducted literature study, SW and LD limitations can be summarized as:

- semantic of terms and concepts are incompatible between different applications often resulting in misinterpretation of concepts and loss of information during information exchanges;
- ontologies are usually created manually by domain specific experts and ontology experts indicating the need for automatically generating ontologies from databases;
- application of the semantic web put demands on the manufacturers to create product data ontology for their products and make their product data available and transferrable as well as shared and reused (Niknam et al., 2019).

## 4 Discussion and Conclusion

In this paper, a literature review was conducted to investigate whether the SW and LD technologies could be a better alternative to exchange information between the building and product manufacturing industries in comparison with the openBIM standards. This goal was achieved by studying the benefits and limitations of these technologies along with the limitations of the existing openBIM information ex-change technologies.

The result showed that the adoption of the SW and LD technologies facilitates an ontology-based information management and sharing. In view of this, ontology development languages provide an opportunity to define the basic terms and relations of domain of interest, as well as the rules for combining these terms and relations. This enables to formalize and represent almost all types of information on the web using a shared vocabulary thereby providing the basis for interoperability between systems. Furthermore, ontologies enable manufacturers to freely describe their products in a homogeneous machine-processable format while making them available for sharing and re-using. The added benefits of using ontologies include reuse, sharing, consistency checking, reasoning over ontology relations to facilitate inferring new conclusion, portability of knowledge across platforms, and improved documentation, semantic queries, maintenance, and reliability.

Upon the development of ontologies, they can be used as a basis for integration of information sources and as a query model for information sources. A significant application of integration of information sources, which is demonstrated by several studies, is the ability to combine product manufacturers' data with the building data. Data generated by these sources can be integrated and made available using the same data format and reachable using common API (Wood et al., 2014). In this regard, manufacturers will have the opportunity to capture real and up-to-date information about the engineering properties of their products and processes using the RDF data model. They can publish this information as a file or in a database, which in both cases, can be searchable via the SPARQL query language and usable by the building industry who have access to the data (Wood et al., 2014). SW and LD technologies can also be used to address the gap between the real-world product description and their abstraction in BIM tools through developing ontologies for different domains required for performance simulations such as construction product standards and regulations, product specification including product cost information, climate data etc. This eventually provides building designers the required information necessary for their design simulation and optimization process.

However, the promising potential of the SW and LD can be fully utilized by the industry when all processes involved in the building lifecycle are operating based on ontology-based information management approach by putting into effect both the top down and bottom up approach of formalizing, standardizing and re-using of concepts and properties. The practical implementation, however, needs to be progressively incremental.

Studies suggest the application of semantic web as supplemental to the existing technologies for rational reasons. One reason is that IFC is already widely used in the industry and supported by large number of BIM software applications. The other reason is numerous actors including engineers, designers, manufacturers etc. use different software applications and have their own way of representing their knowledge. Changing the way these actors work could be an added overload to all parties.

This literature study showed that, even though several research initiatives have put efforts in the application of SW and LD technologies in the building industry, the implementation of these technologies is still open for further research and discussions. Future research, in connection with MAP4Light, will extend this work by creating an ontology for lighting product data and integrating the data in BIM tool for conducting lighting simulations.

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# 3D REVERSE GEOMETRICAL MODELING AND BUILDING INFORMATION MODELING OF HISTORIC BUILDINGS

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**Abstract:** Historic buildings combining functional, historic, scientific, art and social values, deserve scientific conservation. Thus, it is of significance to establish the information archiving. This paper mainly focuses on 3D reverse modeling and building information modeling of historic buildings, laying a foundation for digital archiving and life-cycle maintenance management.

According to the conservation requirements and data characteristics for different parts of historic buildings, three-dimensional laser scanning, UAV aerial photography and close-range photography are selected to acquire point cloud model. And then, the 3D geometric model of a historical building can be created by 3DS Max and Geomagic, and integrated in 3DS Max.

In order to solve the problem of poor generality and large amount of data of geometric model created by reverse modeling technology, an efficient way to transform geometric model to BIM is proposed. Components are automatically identified and classified according to their characteristics with Maxscript language, and the geometric information of components is imported into text files according to the syntax of component's creation in Revit API. Then, a program called Revit API was developed to read the text files and to fulfill data com-pression through parameter analysis of components in historical buildings, and the 3D geometrical model of the historical building was automatically trans-formed into a building information model, which can integrate many types of information such as history, structure and materials.

Finally, taking Shanghai Jade Buddha Temple as an example to verify the validity of the above procedure. Its BIM model is successfully generated and has been developed into a 4D model by integrating the past repair and rehabilitation information.

**Keywords:** Historic Building, Reverse Geometric Modeling, Building Information Model, Data Compression, Clustering Algorithm.

## 1 INTRODUCTION

The lack of original design drawings and technique documents is a common and tough issue during conservation, rehabilitation and utilization of historic buildings. Research work has been carried out to establish the information archiving of historical

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buildings around the world. Conventionally, manual field survey is employed to acquire historical building information(Eslami et al., 2012). Substantial amounts of labor and time are apparently required for historical buildings with irregular shape, complicated texture and structure.

In order to solve this problem, reverse modeling technologies such as 3D laser scanning, Structure from Motion (SfM) also known as terrestrial laser scanning (TLS) and photogrammetry, are used to acquire the information. Agarwal used GPU-accelerated and distributed SfM to reconstruct city-scale point cloud with more than a hundred thousand images of Roma in less than a day and successfully collected geometry information, demonstrates the efficiency of this method(Agarwal et al., 2011). Klein and Bhatla both employed the above image-based method to get point cloud, and further generated CAD model by picking reference points and joining them using lines manually, their result indicated that extracted dimensions were with error about 3%-7%(Bhatla et al., 2012; Klein et al., 2012). Compared with image-based point cloud, laser scanned point cloud has higher accuracy. Golparvar-Fard proved the advantage of 3D laser scanning by comparing eight sets of point cloud models generated by above two methods, the result showed that the accuracy of the image-based point cloud is less than that generated by the laser scanner in both laboratory and actual field experiments(Golparvar-Fard et al., 2011). This method also has limitations, for example, laser scanners are too costly and heavy, causing inconvenience to move around for complete information. Therefore, there were some studies trying to combine these two methods for overcome their own shortcomings. Yastikli proposed the whole documentation process to combine digital photogrammetry and TLS, including data acquisition, data processing and final product, and the resulting textured surface model of the Dolmabahce Palace dome were rich in detail information(Yastikli, 2007). Lerma chose the Upper Palaeolithic Cave of Parpallo as the research object, and with the combined use of close-range photogrammetry and TLS, obtained the textured surface model and successfully exported the elevation plan of the cave(Lerma et al., 2010). Xu and Torres-Martínez also performed the similar modeling workflow(Torres-Martínez et al., 2015; Xu et al., 2014). These studies verify reverse modeling based on multi-source data is a promising idea, lay a solid foundation for the efficient information archiving of historical buildings. However, the generated geometric model only contains vertex with a huge size of data, and more valuable information such as structural monitoring data, history and art, is not included in the model. Most important of all, the model format cannot meet the requirement of information sharing, causing limitations in applications.

Building information modeling (BIM) is suitable for this situation, because BIM model can carry heterogeneous and multi-layered information beyond geometric characteristics, and support a common data structure called Industry Foundation Classes (IFC) which guarantees the exchange of relevant data between different software platforms, improving the generality of the model and ensuring quality and efficiency of the historical building's conservation(Saygi et al., 2013). Biagini presented a BIM-based implementation for the documentation of architectural heritage, they captured data using TLS and photogrammetry, and chose Revit and Autocad for creating solid model and integrated them in Revit, because BIM software require the model consists of solid components, instead of vertex in original geometric model(Biagini et al., 2016). Need to mention that there are many other auxiliary tools can help to create non-standard architectural objects based on point cloud or surface model, such as Rhino, 3Ds MAX, SketchUp(López et al., 2018). After modeling in BIM software, there are many useful applications of BIM model: Crespi collected structural information of an historical masonry building using non-destructive tests (NDT) and minor destructive tests, and import the BIM model into Midas FEA for structural analysis(Crespi et al., 2015); Wang designed a BIM-based model to support fire safety management of buildings, which was capable of evacuation assessment, escape route planning, safety education, and equipment maintenance(Wang et al., 2015); Theiler extended the IFC schema to describe monitoring-related information for BIM-based modeling of structural health monitor (SHM) systems, and did experiment with laboratory test structure, verified the validation of the proposed IFC model on SHM(Theiler and Smarsly, 2018). These works demonstrate that BIM model can provide comprehensive data shared among different platforms for further applications and surely can make conservation more efficient.

Based on these previous researches, this study proposes a new workflow on multi-source data based reverse modeling and an automatic transformation program to bridge the gap between geometric model and information model. And the informatization of Jade Buddha Temple is taken as an example to show the feasibility of the procedure and the wide application of its information model.

# 2 Reverse Reconstruction of Geometric Model Based on Multi-Source Data

## 2.1 Multi-source Data Collection

Considering the complex shape of historical buildings, data should be collected with multiple methods, ensuring data integrity and accuracy. In this study, a 3D laser scanner was used to complete the overall scanning of the main part of the building; The hand-held scanner and camera were used to focus the sampling of architectural details (such as carvings, textures, etc.) to improve the accuracy of model; The UAV collected data of hidden part such as the historical buildings' roof to make up for missing data.

## 2.2 Data Processing

### 2.2.1 Structure from Motion and Multi View Stereo

SfM and MVS are classical computer vision technologies. The geometric relationship between image points and object points can be solved based on corresponding image points, so as to obtain a dense point cloud of the measured object, as shown in Figures 1.

Figure 1: Twenty Heaven Statue in the Mahavira Hall.

### 2.2.2 Point Cloud Filtering and Reduction

Based on the original point cloud, data filtering algorithm can be used to effectively remove noise points. In addition, it is also necessary to comprehensively use the curvature sampling method and the preserved boundary method to reduce the huge point cloud data (Lee et al., 2001).

### 2.2.3 Multi-source Data Fusion

Through the data processing introduced above, the geometric information in the form of point cloud can be obtained. However, for the geometric information obtained by different methods, there are still problems such as data separation, excessive data volume, and lack of topological relationships, which need to be solved by the following ways.

#### *2.2.3.1 Point Cloud Fusion*

Referring to the relevant theories of point cloud data registration and digital image matching, the point cloud collected by the 3D laser scanner and the digital image captured by the camera also have a lot of overlapping parts. Through searching for corresponding points, the rigid body transformation of the data in different coordinate systems can be carried out, and the 3D laser scanning point cloud data and image point cloud data can be merged together. Figure 2 shows point cloud of the Mahavira Hall.

Figure 2: Point cloud of the Mahavira Hall.

#### *2.2.3.2 Point Cloud Segmentation*

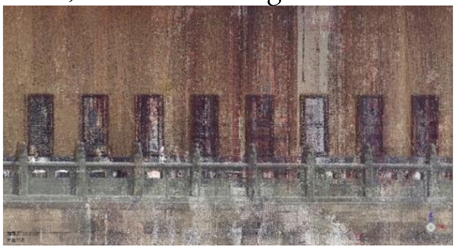
Although the noise and the density of point cloud data have been effectively reduced after data filtering and data reduction, the fused point cloud data still inevitably has a problem of excessive data size. Reasonable segmentation of the point cloud data is needed to facilitate subsequent applications. In this study, segmentation is performed by edge-based and region-based segmentation algorithms and manual operation in a point cloud post-processing software called Geomagic. In this way, the point cloud data of the Mahavira Hall can be segmented into two parts, the roof structure and the substructure, as shown in Figure 3.

(a) (b)

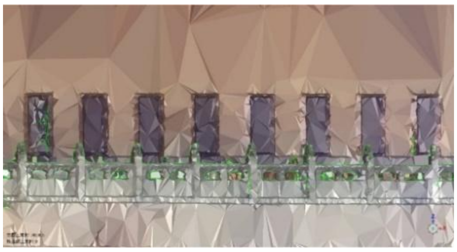
Figure 3: (a) Point cloud of roof. (b)Point cloud of substructure.

#### *2.2.3.3 Polygon Mesh.*

Although high-density point cloud data can express the three-dimensional geometric information of historical buildings, it is still a large number of dense discrete points, which don't belong to structured information. Based on the point cloud data of historical buildings, the component surface can be approximated by the Delaunay triangle mesh method, the surface model and topological relationship of historical building components are generated, as shown in Figure 4.



(a)



(b)

Figure 4: (a) A part of point cloud. (b) A part of polygon mesh generated.

### 2.2.4 Reference Modeling

Reference modeling is the process of reconstructing a geometric model based on polygon mesh data. 3DS Max is often employed to finish this step due to its powerful modeling and rendering function.

Components of a historical building can be divided into two categories by the geometry complexity, i.e., the core category contains the main building and structural components, such as walls, columns, roofs, etc., most of these components are the splicing or deformation of basic geometry, which can be created by 3DS Max's polygon modeling function, as shown in Figure 8; the affiliated category contains the decorative parts in historical buildings, such as mural, Buddha statues, etc. These components are completely irregular objects, and it is difficult to manually model directly. The only way is to import the polygon mesh into the 3DS Max software for fusion, and the polygon mesh is created by the method explained in previous part, as shown in Figure 6-7.

### 2.2.5 Texture Mapping

After the mesh model is transformed into a solid model, in order to improve the fidelity of the model, texture mapping is usually required. Texture mapping is the mapping of color on texture image to the corresponding part of solid model's surface depending on the relationship between the point cloud's intensity information and digital image's color information. In 3DS Max, the material editor and UVW map modifier can be used to complete the mapping, Figure 8 shows the overall model of the Mahavira Hall after the texture mapping, and the reconstruction of the geometric model is completed.

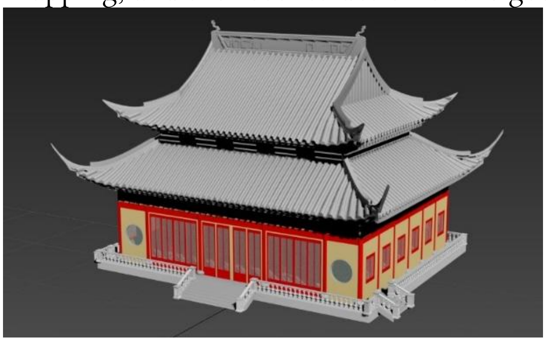


Figure 5: 3DS Max model of the Mahavira Hall. Figure 6: Three Buddhas' models

Figure 7: Twenty Heaven Statues' models.

Figure 8: The textured model of the Mahavira Hall.

## 3 PRINCIPLE OF AUTOMATIC MODEL TRANSFORMATION

The geometric model of historical buildings contains a lot information of point, line, and area, most of which is not necessary for the description of the model, so data compression is needed. Moreover, it is difficult for the geometric model to incorporate other building information and its format is also difficult to meet sharing requirements.

In order to solve the above problems, an automatic conversion program is developed based on MAXScript and Revit API to convert the geometric model in 3DS Max into the information model in Revit. Revit was chosen here because it supports subsequent extensions based on the IFC standard.

The conversion program includes four steps: identification and classification of component types, geometric information extraction, element creation, and information attachment.

### 3.1 Identification and Classification of Component Types

#### 3.1.1 Main Structural Components-Geometric Recognition

The main structural component types of historical buildings include beams, columns, walls, and slabs. Most of these components have their own standard geometry which size characteristics are easy to be identified. So, the type of the component can be determined by the geometry type and size. For example:

The wall in the 3DS Max model belongs to the cuboid class. Its width is generally less than 300mm and its height is greater than 1000mm. After identification, the components could be stored in the corresponding array.

The geometry type of the rectangular beam belongs to the cuboid class. Its width is generally less than 500mm, and its height is less than 1000mm, and its length is more than three times of the height. Define an array named as “rectangularBeam”, which can record these rectangular beams.

The geometry type of floor slab belongs to the cuboid class, while its width is generally greater than 1000mm, and its height is generally less than 200mm. Define an array named as “Floor”, which can record these floor slabs.

The geometry types of circular columns and circular beams belong to the cylinder class, and their height is generally greater than 3 times of the radius. A component which axis direction is vertical can be stored in an array called “circularcolumn”. And one which axis direction is horizontal can be stored in an array called “circularBeam”.

### 3.1.2 Complex Components-Name Recognition

The historical building also contains other various complex parts, such as roofs, murals, bucket arches, etc. Such parts have complex shapes, different model attributes and characteristics, which cannot be identified by geometry types and sizes. It is the only way to identify them by name.

The following MAXScript code traverses and identifies the objects whose name contains "Roof", "Mural", "BucketArch", or "StonePier", and then groups them into the corresponding array respectively, to realize the identification of components with complex shapes:

```
Roof = $ * Roof * as array
Mural = $ * Mural * as array
BucketArch = $ * BucketArch * as array
StonePier =$ * StonePier * as array
```

## 3.2 Geometric Information Extraction - Clustering Algorithm

For components with the same designed size, they definitely have small differences in the real size due to possible construction errors, measurement errors, or modeling errors. This not only brings trouble to the modeling, but also doesn’t meet the requirements of application, so the size needs to be standardized by clustering algorithm.

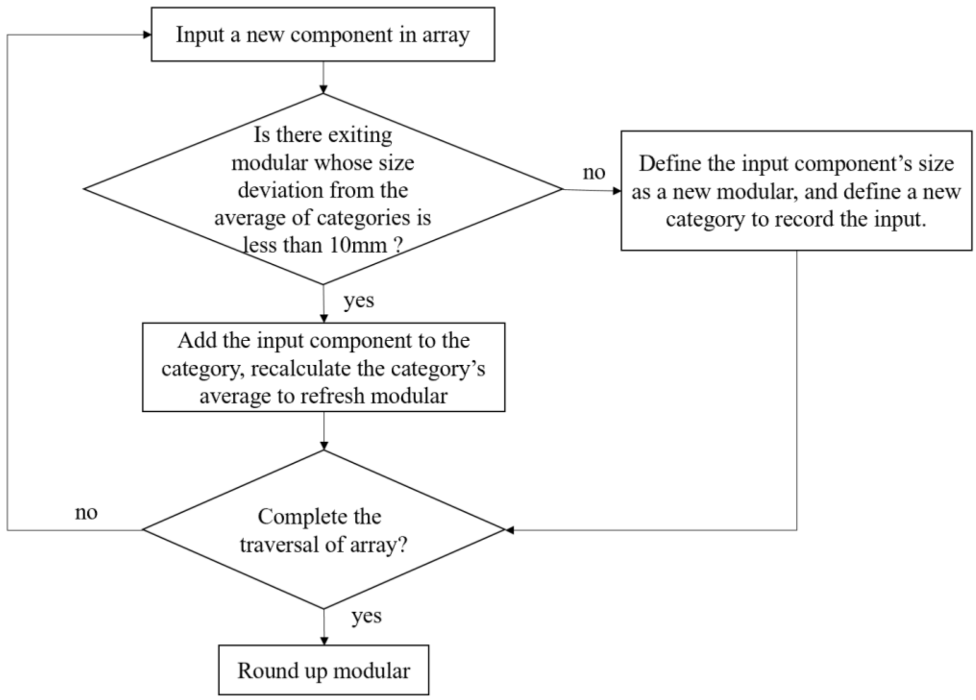



Figure 9: Flow chart of component clustering algorithm.

In GB50206-2012, "Code for acceptance of construction quality of timber structures", the acceptable error for the manufacture and installation of beams, columns and other components are specified as 5mm-10mm. Considering the crude of ancient construction technology, allowable error of geometric model can be appropriately enlarged to 10mm. That means size with errors not exceeding 10mm can be standardized as a particular size which also can be called modular.

Therefore, for a specific component type, by traversing the component' array and clustering, components with the size of a deviation of less than 10mm can be classified into one category, the flowchart is shown in Figure 9.

The obtained modular should be attached to the corresponding category and stored in a text file for modeling, while the original discrete data should be stored as the measured parameter values for subsequent information attachment and structural maintenance.

## 3.3 Element Creation

In Revit, the components such as columns, foundations, windows, and doors, can be created by calling the Revit API. So, by introducing the data information in the text file created before, a C # program can fulfill element creation automatically.

The key problem is to obtain the parameter value imported into the creation function. After getting the necessary information, running the function can fulfill the whole creation, and the created elements need to be labeled for subsequent use.

### 3.3.1 Creation of Reference Elements

There are functions which can create reference elements, what is needed is elevation and grid information which can be identified and obtained from 3DS Max model.

Elevation value can be determined by the centroids' Z coordinate value of main structural member.

Grid refers to the planar positioning of the components, and the positioning axis is generally the centerline of the columns in a building plan. Therefore, the grid lines' information can be obtained by connecting the center point of the column. In order to facilitate the operation, the same arrangement of grid lines is arranged on each level.

### 3.3.2 Instance Creation Based on Model Lines

Components such as walls, slabs, and beams are created based on model lines. The required reconstruction information includes model lines, types, elevations, and structural features. Wall reconstruction is taken as a typical example, and the wall creation function is shown in Figure 10(a).

Analyze the parameters of the function one by one: "document" is the current Revit model file; "curve" represents the wall model line and determines the length of the wall, can be determined by the coordinates of the midpoints of the two short sides of the wall bottom; "wallTypeId" represents the wall type, determined by the wall width; "LevelId" represents the ID of the elevation where the wall is located, determined by reading the array that stores the elevation ID number when the elevation is created; "height" represents the height of the wall, determined by the height of the cuboid; "offset" represents the bottom offset, generally defaults to 0; "flip" represents whether to flip, the default is generally false; "structural" represents the wall structure, "true" represents the load-bearing wall, "false" represents the non-load-bearing wall, considering wood structures are generally filled walls, so the default is false.

Therefore, for each cuboid identified as a wall in 3DS Max, it is necessary to extract the coordinates of the two short sides of the bottom of the cuboid, the width of the cuboid, the height value, and the elevation number corresponding to the Z coordinate of the cuboid position. “wallTypeId” is determined by traversing and comparing width of each wall type with the width of the extracted cuboid, or in another word, determined by wall thickness.

### 3.3.3 Instance Creation Based on Position Coordinates

“NewFamilyInstance ()” in the Revit API provides methods for creating instances based on position coordinates of components. Take the creation of a cylinder column in Chinese traditional buildings as an example, its creation function in the Revit API is shown in Figure 10(b).

Analyze the information required one by one. For each cylinder identified as a column in 3DS Max, the program needs to extract the cylinder position coordinates, the cylinder radius and height, and the elevation corresponding to the cylinder position Z coordinate. “structuralType” is defined as “StructuralType.Column” by default. “symbol” is actually the column type, can be determined by traversing all the family types whose name string contains a "circular column" and comparing the radius and height of the cylinder.

```
C#
public static Wall Create(
        Document document,
        Curve curve,
        ElementId wallTypeId,
        ElementId levelId,
        double height,
        double offset,
        bool flip,
        bool structural
)
```

(a)

```
C#
public FamilyInstance NewFamilyInstance(
        XYZ location,
        FamilySymbol symbol,
        Level level,
        StructuralType structuralType
)
```

(b)

Figure 10: (a)Wall creation function (b)Column creation function.

### 3.3.4 Instance Creation Based on Host

The Revit API provides a host-based instance creating method, which is suitable for the creation of doors and windows embedded in the wall. Take the window as an example, its creation function is shown in Figure 11.

Analyze the information contained in the function one by one. For each object defined as a window in 3DS Max, you need to extract its position coordinates, the length, width, and height of the window, the corresponding number of the host wall to which the window belongs to, and the host wall. “structuralType” is defined as “StructuralType.NonStructural” by default. The length, width, and height of the window can be determined by traversing the coordinates of all the vertices of the window grid object to determine the XYZ direction range. “symbol” is actually the form of window, can be determined by traversing all the family types whose name string contains a "window" and comparing the length, width, and height of the form. The host wall and the corresponding elevation of the host wall may be determined by the ID numbers stored in the wall creation.

```csharp
C#
public FamilyInstance NewFamilyInstance(
        XYZ location,
        FamilySymbol symbol,
        Element host,
        Level level,
        StructuralType structuralType
)
```

Figure 11: Window creation function.

#### 3.3.5 Supplementary Creation in GUI Interface

The above methods have been able to meet most of the modeling requirements of historical buildings, but the Revit API does not provide all the data creation interfaces in Revit. Therefore, some components need to be created in GUI interface. For example, Buddha statues have complex and different shapes, and it is difficult to restore them perfectly using the family tools. However, such elements have little effect on the structural maintenance in the whole life cycle, and it is acceptable to import the relevant 3DS Max model into Revit as an external symbol and to fulfill the building information model manually.

### 3.4 Automatic Information Expansion

Nowadays, a large amount of historical building information, especially the structural inspection results, are stored in the form of electronic documents. It's not hard to extract information and attach them to BIM model by a computer program.

Shared parameters are parameter definitions that can be used in multiple families or projects, which are useful for information attachment. The procedure of the shared parameter definition, binding and parameter value setting is shown in Figure 12.

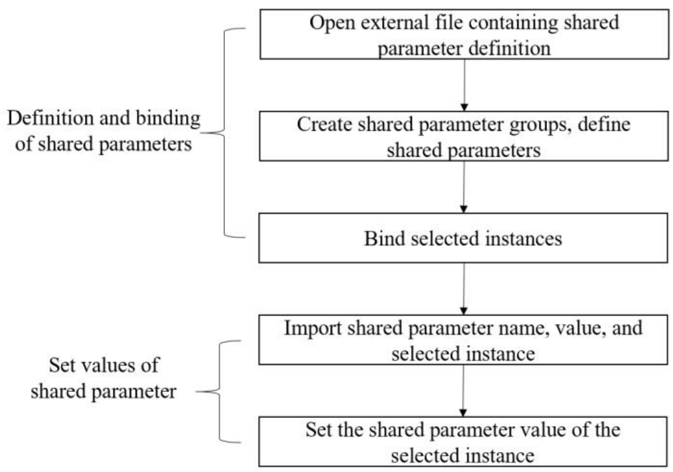



Figure 12: Shared parameter definition, binding and parameter value setting.

Based on the above principle, a C# program is coded to realize the automatic information expansion. The main steps of the process are shown in Figure 13.

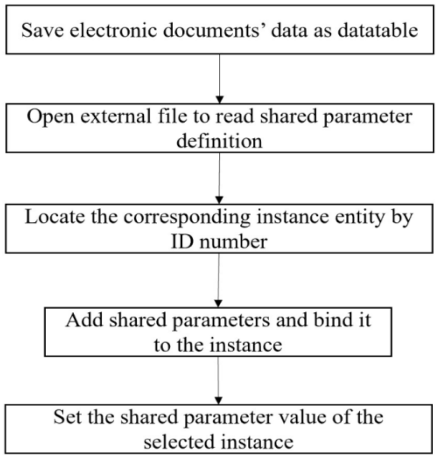



Figure 13: Flow chart of shared parameter definition and assignment.

## 4 APPLICATION OF SHANGHAI JADE BUDDHA TEMPLE'S INFORMATION MODEL

Floor plans can be automatically generated from the Revit model, as shown in Figure 14; Panoramic map of the Jade Buddha Temple can be created using Pano2VR for tourism promotion and navigation, as shown in Figure 15.

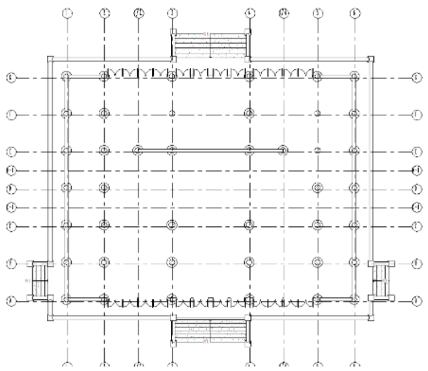


Figure 14: Ground floor plan. Figure 15: Panoramic map of the Mahavira Hall.

If the time-dependent information is integrated to the Revit model, so-called "4D" information model can be generated, which is useful for rehabilitation and maintenance throughout the life cycle. According to the historical documents of the Jade Buddha Temple, the Temple went through 7 repairs, 1 large-scale expansion and recent Panning. So, divided the information model of the Jade Buddha Temple into 12 stages on the time scale and the rehabilitation information can be integrated at the corresponding stage, as shown in Figure 16.

Figure 16: Model of the Mahavira Hall in Panning Stage.

## 5 CONCLUSIONS

In this research, multi-source data collecting, processing and fusion for 3D reverse modeling were performed, and geometric model was created by reference modeling. Then, its BIM model was generated by the automatic conversion program which can convert the geometric model in 3DS Max into the information model in Revit and attach information, because BIM model can not only reduce data size, but also increase the amount of model information and improve the generality of the model. The application on Shanghai Jade Buddha Temple successfully verify the feasibility of the procedure and demonstrates the high potential of the workflow on lifecycle management of historical building.

However, problem still remains: reference modeling rely on a lot of manual operations. To solve this problem, future research will focus on semantic segmentation of point clouds using deep learning, which can separate all components from each other in point cloud model. This is helpful for component identification and geometric information extraction directly from segmented point cloud, which make automatic conversion from point cloud into the information model possible.

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# REAL-TIME EVALUATION OF ROOM ACOUSTICS USING IFC-BASED VIRTUAL REALITY AND AURALIZATION ENGINES

**Simon Swanström Wyke[1], Kjeld Svidt[2], Flemming Christensen[3], Jesper Bendix Sørensen[4], Torgeir Mithun Fadnes [5] and Rasmus Lund Jensen[6]**

**Abstract:** Virtual Reality and Auralization are commonly used for separate types of simulation and evaluation in todays' building industry. Combining the two technologies in order to evaluate room acoustics through real time auralization is still a novel approach in the industry. Common practises in designing room acoustics were identified in a case company, and used in the developing of a combined audio-visual system. The case company, additionally, participated in the testing of the system. The system is developed to support dialog between designers and end-users, with no or limited acoustic expertise and to widen the use of virtual reality with auralization.

**Keywords:** Virtual Reality, Auralization, System Development.

## 1 INTRODUCTION

The indoor environment has become an increasingly important topic in the building industry in recent years. This has led to increased research into how room acoustics influences people's performances and how auralization can be used for simulation of room acoustic (Reinten *et al.*, 2017). In this paper, we define Auralization as the process of making an acoustic space audible, thus enabling listening to the space under design. (Kleiner, M.; Dalenback, B-I.; Svensson, 1993; Savioja and Svensson, 2015).

The increased use of 3D models with attached building information (Building Information Modelling, BIM) in the building industry can facilitate the transfer from 3D-design models into Virtual Reality (Bille *et al.*, 2014; Wang *et al.*, 2014; Du *et al.*, 2018; Sebastian *et al.*, 2018). Recent years' development of VR and the reduced cost of both VR hardware and software has enabled a wider use of it as an interactive design platform, allowing people to interact within the Virtual Environment (VE) (Svidt and Sørensen, 2012; Petrova *et al.*, 2017; Rasmussen, M.; Gade, A.; Lund Jensen, 2017), and contribute to finding improved design solutions.

BIM based VR however, often has issues such as missing material information and that it can be a time consuming process going from a Computer Aided Design (CAD)

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format into VR. This is the case using both proprietary and open source data formats in the data transfer (Du *et al.*, 2018).

Most VR applications used in the building industry, focus mainly on the visual rendering of building geometries (Pelzer, S.; Aspöck, L.; Schröder, D.; Vorländer, 2014; Vorländer, M.; Schröder, D.; Pelzer, S.; Wefers, 2015). The use of sound stimuli can nevertheless augment the visual perception significantly (Schröder, 2011), and other engineering branches using VR have experienced that audio information can be more important in VR applications than the visuals of a Virtual Environment (VE) (Brooks Jr., 1999; Whyte, J.; Nikolic, 2018). Pitt et al., (2005) furthermore emphasise that it would be wrong to assume that VE's must represent full visual realism of the geometry presented in VR to be effective (Pitt, M.; Goyal, S.; Holt, P.; Ritchie, J.; Day, P.; Simmons, J.; Robinson, G.; Russell, 2005; Swanström Wyke, Christensen, *et al.*, 2019).

Adding the room acoustic model to the 3D model of the building's geometry makes it possible to do auralization (Savioja and Svensson, 2015). Combining visualization and audio further makes it possible to attain end- user evaluation early in a design process, get empirical measurements of user's performances, and do iterative user testing (Gould and Lewis, 1985; Kim, Cha and Kim, 2016) not only with respect to the visual and geometric design of a room, but also the acoustic design.

## 1.1 Evaluation of room acoustics

Evaluation of room acoustics mostly occur in acoustically challenging spaces, such as concert halls, train stations, airports and theatres, and traditionally focuses on music perception and communication through speech (Pelzer, S.; Aspöck, L.; Schröder, D.; Vorländer, 2014; Vorländer, M.; Schröder, D.; Pelzer, S.; Wefers, 2015). Savioja and Svennson (2015), however, argue that acoustic traits of educational buildings, public venues and homes are important to evaluate as well.

How the acoustics of a room affect people and their performances depends on what type of room is under consideration, what tasks are performed in the room in addition to the habits of the room user(s) (Haapakangas *et al.*, 2014; Reinten *et al.*, 2017). Including both clients and end-users in the acoustic room evaluation during design, providing a valid perspective towards such dependencies, allowing for better acoustic design.

The sound environment is what influences task performance of people in a room the most, not the acoustic design. The design of the room acoustics, however, influences the sound environment (Reinten *et al.*, 2017), clarifying the importance of focus on room acoustics during building design.

Room acoustics does not only focus on the airborne sound insulation and structural properties. But also structure-born excitation from HVAC, household appliances and electrical equipment, (Vorländer, M.; Schröder, D.; Pelzer, S.; Wefers, 2015) and sound generated by such, distributed in a room via reverberation.

## 1.2 Use of Auralization

Since the beginning of the 1990s, computer simulation of room acoustics has been feasible (Kleiner, M.; Dalenback, B-I.; Svensson, 1993). Before computers were used in this regard, acoustic design had to be based on equations providing the sound field average, or investigations in scale models. However, due to the sensitive perception of humans, more specific investigations are needed in order to match the desired performance of the client and end- user(s) of a room (Pelzer, S.; Aspöck, L.; Schröder, D.; Vorländer, 2014).

Some acoustic problems can be solved by acoustic engineers solely based on calculations and analysis. Sometimes however, the process of particular auditory perception is not finally understood. In such cases auralization can contribute to finding a solution (Pelzer, S.; Aspöck, L.; Schröder, D.; Vorländer, 2014).

One of the important phenomena in room acoustics is reverberation (Pelzer, S.; Aspöck, L.; Schröder, D.; Vorländer, 2014; Xia *et al.*, 2015). Prediction of reverberation can be done rather precisely by using the room volume and the average absorption coefficients for each surface (Kuttruff, 2000; Pelzer, S.; Aspöck, L.; Schröder, D.; Vorländer, 2014).

Both 3D models with building information attached and databases of absorption coefficients exist in most engineering companies. We therefore investigated how data are generated and used, in a case study, to design a VR with Auralization (VRA) system for the building design process, based on common practise in an engineering company with branch offices in both Denmark and Norway. The company participated in the case study inquiry, which lead to the iterative development and tests of the VRA system, presented in this paper.

# 2 METHODOLOGY

## 2.1 Empirical inquiry

Multiple employees from the Danish and Norwegian branch offices of the company were interviewed, to investigate current design processes in the company, and attain understanding of how data is transferred within their project organisation.

Empirical data were acquired through the contextual design methodology, as described by Beyer and Holtzblatt (1997).

## 2.2 Test of Virtual Reality with Auralization system

A VRA system was developed, based on the Unity 3D engine, Epiito software and AM3D spatial audio software (Europe Goertek, 2019) as shown in figure 1.

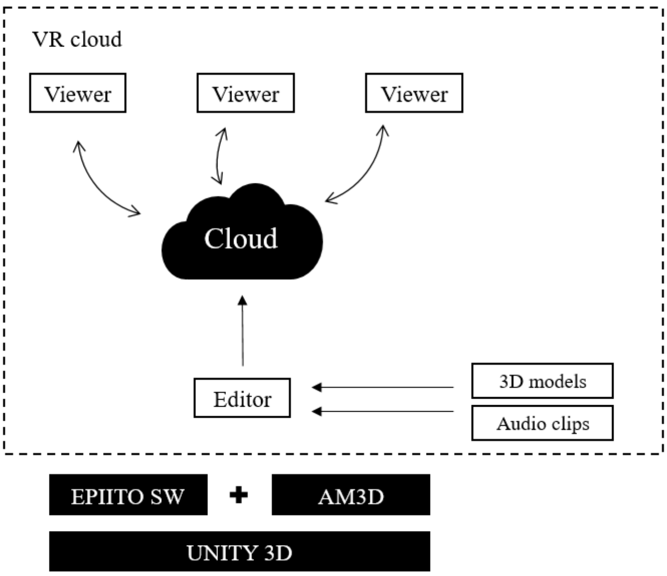


Figure 1 Flow model describing the system context of VRA, in this scenario the AM3D auralization engine is used.

The VRA system has a distinct focus on user interaction, visual presentation of building geometries and auralization. It furthermore reads the Industry Foundation Classes (.ifc) format, allowing system interoperability with multiple building and construction-modelling applications used in the building design industry, in a non-vendor specific format.

Acoustic rooms in VR are generated from IFC-spaces and anechoic sound-sources can be placed in the acoustic space, allowing for auralization.

The game engine Unity allows for at least two different auralization engines – Resonance Audio and AM3D Spatial audio. Both engines allow positioning of sound sources and simulation of reverberation based on room dimensions and material properties. Both the AM3D and Resonance auralization engines were tested in this study.

Based on initial tests of VR with Auralization, test scenarios were selected, to assess realism and functionality of the VR- auralization system. As the perception of sound differentiates from person to person, and tends to be sensitive (Vorländer, M.; Schröder, D.; Pelzer, S.; Wefers, 2015), the tests were based on how the test persons perceived the room acoustics in VRA.

Sound from electronic equipment, household appliances and a ventilation system were recorded in an anechoic room, to eliminate influence from reverberation, to make the recordings controllable by the auralization engine (Swanström Wyke, Christensen, *et al.*, 2019; Swanström Wyke, Sørensen, *et al.*, 2019). The audio clips were recorded to initiate the build of a sound database for use in Virtual Reality with Auralization (VRA) systems. This database is still in the early stages of development, but could potentially aid the industry, allowing firms already using VR technology to also include auralization.

The anechoic audio clips in .wav format were inserted into VR using the AM3D suite or the Resonance Audio auralization engine. The absorption coefficients of surfaces the sound clips were played from are manually adjusted based on the materials of the room surfaces and the measured reverberation. The auralization engines only allow specification of one overall absorption coefficient per surface.

Both end-users, researchers and system developers, engaged in informal listening tests and informal user experience tests.

All test scenarios were presented in VR through Oculus Rift VC1 and Oculus Quest head mounted display (HMD) and Seenheiser PC 363 D as well as Bose QC35 ii headphones as listening device, calibrated using a sound-level calibration box, shown in figure 2, developed as part of the system development (Swanström Wyke, Sørensen, *et al.*, 2019).


Figure 2  Calibration box designed for calibration and level adjustment of the headphones used with the system

As the two auralization engines used with the VRA system do not support surface sound-sources, but only allows use of point sources, the tests were performed to find a sound-source placement technique providing the experience of an equal distribution of sound amongst sources in a room.

In the sound distribution test, five respondents tested the possibility of simulating an entire surface, e.g. a window or a wall as a sound source by means of a limited number of point sources. The respondents were exposed to a test scenario with 21 sound sources with and without windows and 7 sound sources, placed in a grid on a wall surface as shown in figure 3. The respondents then walked by the wall, and around in the area in front of the sound sources in order to evaluate the degree of realism of the acoustic room presented.

The second sound test included another scenario with a single sound source, designed to follow the movement of the respondent's avatar. Like in the other tests, respondents again moved around the test area, experiencing the acoustic room presented through VRA. This time however, with the sound source following the avatar. This allowed for an apparently even distribution of sound, as the avatar's movement did not lead to different sound sources being prominent experienced when moving around in the test area.

In the VRA system, a maximum of 512 sound sources can be placed in the VE. This number is per avatar immersed into VR.

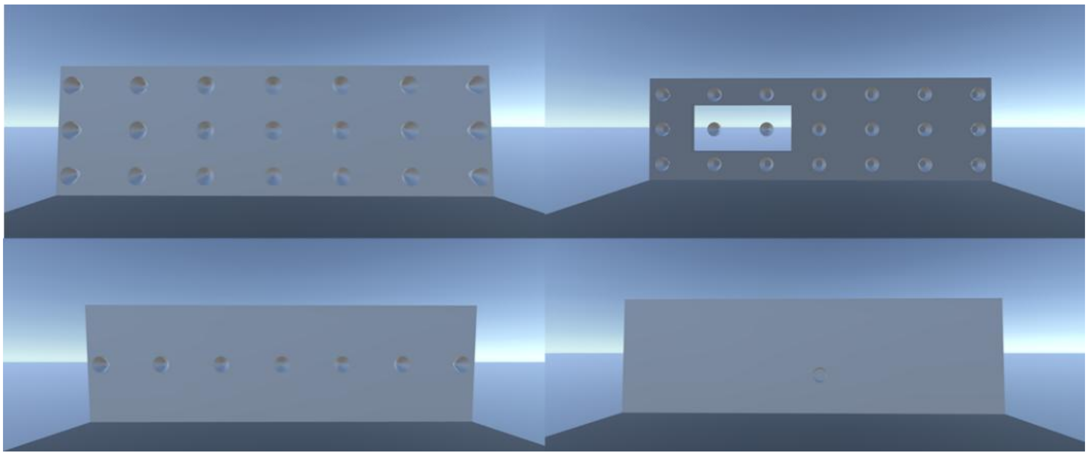

Figure 3 The four sound distribution test-scenarios

## 2.3 End-user test and presentation

In the end-user, test and presentation 17 respondents participated in informal user experience tests. The scenario presented, was a lecture room at the Department of the Built Environment at Aalborg University, and included sound sources placed in four locations in the room. The scenario was used in earlier test-sessions as well, allowing some of the respondents whom had participated in earlier testing, to compare functionality, realism and intuitiveness of the system.

The four sound sources placed in the test-scenario were:

1. Speech playing from a non-playable character, placed in the VE.
2. Sound from electronic equipment.
3. Sound from construction work from a window.
4. Sound from neighbouring room through an open door.

The scenarios were presented to the respondents in two versions. One with an open window in the room and one with the window closed.

# 3 RESULTS

## 3.1 Case company inquiry

In the company participating in the case study, acoustic designing is typically a collaboration between architects and acoustic engineers (figure 4). The design process they conduct is iterative, and involves evaluation of 2-3 scenarios with respect to acoustic room design. The focus on acoustics is, however, dependent on the building type. Concert halls, theatres and other sound sensitive buildings are treated with more concern than e.g. office buildings and housing estates, as is also common practise in the industry (Pelzer, S.; Aspöck, L.; Schröder, D.; Vorländer, 2014; Vorländer, M.; Schröder, D.; Pelzer, S.; Wefers, 2015).

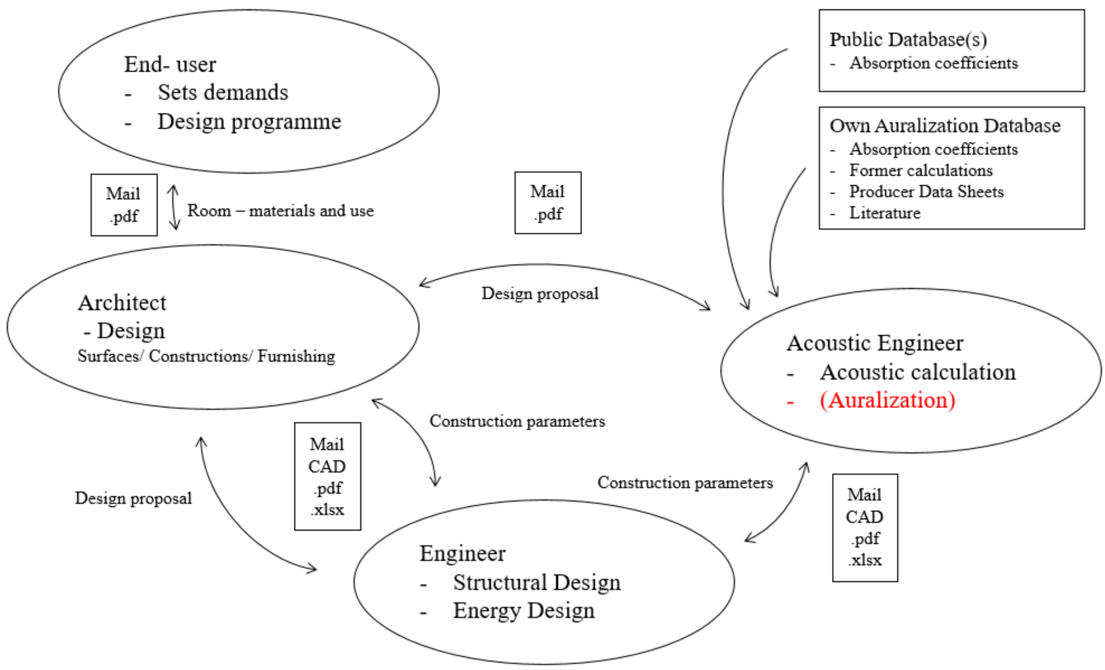


Figure 4 Flow model of the current design process with respect to acoustic design, in the case company.

In the case-company, most building-design projects are modelled in 3D and data are primarily exchanged in the proprietary (Revit) format .rvt. The .ifc format is also used in the company, mainly in the Norwegian branch in which the use is standard procedure. The format is also occasionally used in the Danish branch office.

The company primarily relies on the building regulation, when designing room acoustics. Clients, however, sometimes demand a better acoustic environment than the building regulations define. Such increased demands are formulated in the design brief of a project. The design brief is not always present in Danish design projects, it is, however, mandatory on projects in Norway. According to the respondents, demands set by clients rarely extent the building regulation's demands to acoustic design in Norway, but occasionally happens on projects in Denmark.

In acoustic design projects, time and money often limit the depth in which acoustic evaluations of rooms are performed. The company, therefore, primarily focusses on the most sensitive rooms, whilst keeping most of the acoustic evaluation on building level.

With respect to technical installations in a building's design, selection of a design proposal is mainly based on dialog between the architect developing proposals, and the acoustic engineers calculating the effect of said design.

Dialog, combined with results from analysis and calculation tools, are currently the key tool the design team uses to evaluate and find the optimal acoustic design solutions. The dialog and general communication between parties in the company consist of multiple exchange formats, going from mail, PDF, CAD formats (.ifc, .rvt, .dwg) to .xlsx and .docx.

Acoustic calculations of reverberation are based on absorption coefficients found in the company's own database which consist of calculations done on previous projects, literature and supplier data sheets. In some occasions, the company also uses public databases.

Sometimes, however rarely, auralization is used by the company, allowing the design team, client(s) and end-user(s) to listen to the proposed or selected acoustic solutions. The auralization currently used in the company, is nevertheless without visual supplement.

During the interviews, the respondents recounted that real time Virtual Reality with auralization could be an aid in explaining design options to clients and end-users and support the communication between parties on a project. A notion the respondents also noted during earlier systems tests (Swanström Wyke, Sørensen, *et al.*, 2019).

User feedback is often relevant in design projects for the company, as surface materials demanded by the client or end- users, affects the acoustic performance of a room. As much of the material selections are also based on the visual preferences of clients and users, a system supporting auralization must also include the visual link. The respondents did not rate the realism of the visualization in VR, as important, as the realism of the auralization during testing.

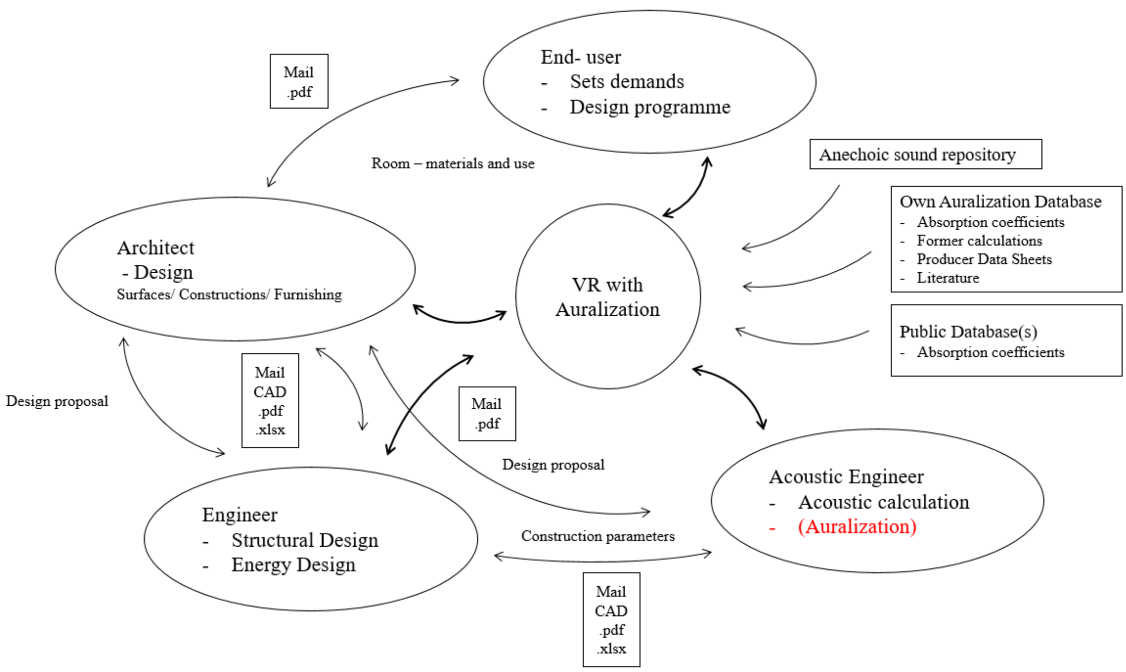


Figure 5 Exchange of information using VR with Auralization as the centre of communication with respect to room acoustics.

Finally, the respondents not½ed that the a VR based system can also work as the centre of communication on a project (figure 5), and allow for better evaluation and use of building models on a project, not limited to the acoustic preferences, creating indirect benefits through the use of the system.

## 3.2 System tests

The VRA system was tested multiple times during its development. The tests facilitated an iterative design process of the system, allowing end-users, researchers and developers to monitor the evolution of the system. Figure 6 shows a developer introducing and instructing a respondent in how to use system.


Figure 6 Developer introducing use of head-mounted display and controllers to respondent.

In the sound distribution test, the single sound source solution, which followed the avatar's movements in VR, proved to be the most feasible solution for the VRA system, as sound was experiences as evenly distributed when the test persons moved around in the test area. The single source solution will additionally be an easier solution to automate, as only one source needs to be controlled. Only having one source playing will furthermore result in shorter loading time when opening or loading in a VRA.

In scenarios with multiple sound-sources placed in a fixed grid on a surface, the test persons experienced an unequal distribution of sound from the surface. This allowed the respondents to be able to differentiate the sound sources from each other, instead of experiencing an evenly distributed sound. Such solutions were, therefore, not selected for the further development and testing.

The end-user test and presentation resulted in positive reactions by the test persons. The test persons, however, pointed out some concerns.

One of the main concerns with respect to use of the system was the process of converting computer aided design (CAD) files into VR in a feasible way. The converting of CAD should according to the test persons not result in an increased workload, but be easy and intuitive to do.

Another issue the respondents addressed was ensuring the quality of auralization when moving from one virtual room to another, as sound sources muted promptly in the test-model when test-persons were moving from one room to another. This limited the realism of how sound-transfer between rooms was experienced in the system by the respondents, when compared to how sound-transfer is experienced in the real world.

Experiencing auralization whilst at the same time seeing the visual surroundings of the sound sources, made it possible to evaluate room acoustic of the test scenario, in a tangible fashion, indicated by the test persons. When sound is emanating from a transmission through a wall or other building elements, ensuring an equal distribution of sound in the VRA system was a primary concern of the test persons.

The test further revealed that the respondents found the system to be realistic and accurate, and well suited to implement in the case-company.

In summary, the respondents requested further development of:

- A solution for communication between users in a multi-user setting, in the virtual environment.
- Improved possibilities of handling sound from adjacent rooms.
- Alignment of user-interface with related tools.
- Direct connection between the VR with Auralization system and BIM-authoring tools.

# 4 Discussion

## 4.1 The IFC-based Virtual Reality with Auralization

The system VRA system is designed to allow real-time evaluation of room acoustics, by acoustic non-experts. The developed system makes it possible to generate acoustic spaces based on the IFC code automatically, by pressing a button in the VRA user interface. This makes it easy to go from CAD into VR. It, nevertheless, require the case-company to include IFC in its standard data exchange procedure on design projects.

The sound source mechanism used in the system, has a maximum number of 512 sound sources. The sound sources are loaded into the system based on the distance between avatar and the sound source, reducing the computational capacity needed to run the system.

The interviews revealed that auralization is already used in room acoustic design, in some rare occasions in the company. The respondents were eager to use Virtual Reality with Auralization, allowing designers, clients and end-users, and implementing it as a supplement to the acoustic calculations already performed in the company during building most designs.

In most of the projects designed by the company, building geometries are modelled in Autodesk Revit. This allows them to both visually program the building components and include properties including acoustic parameters usable for an automated VRA generation process.

As 3D models are already being utilized as part of the case company's current work processes, the only matter to address regarding VR is how to export the 3D model with needed parameters and values, into a VR compatible format, in this case .ifc.

The use of .ifc in the case- company is, however, not a de-facto standard in al branch offices. This is a challenge in implementation of the VRA system in the company, as the 3D model import in the VRA system is based on the .ifc format.

Another issue the company faces with respect to the use of their design models for VRA, is ensuring the needed level of development of geometry and information content of the model, to generate a realistic VE

### 4.2 Cost involved with use of VRA

There are costs associated with both developing, implementing and using VR with Auralization.

In order to use VR, both head mounted display (HMD); headphones in a good quality and a relatively powerful computer are needed, unless Oculus Quest is used. The cost of hardware is approximately 1.200 to 2000 €. This cost, however, seems small compared to cost of changing both procedures and mind-sets in the case company, involved with implementing the VRA system.

The empirical inquiry in the case company revealed that .ifc is not always the format used to exchange 3D models in their design projects. As the VRA system is based on 3D model import in the .ifc format the building model exchange processes in the case company must therefore be updated. This needs to include demands describing the level of development of models exchanged in the .ifc format and making the use of .ifc a common practise.

Anechoic recordings are not easily accessible and must therefore be available before auralization can become common practice. This process can be costly, as the recording of sounds in an anechoic room or chamber both takes time and demands expert knowledge.

## 5 Conclusion

This paper presented an overview over common practises in the building industry with respect to room acoustics, based on interviews performed in a case company. Through a combined audio-visual engine, Auralization engines controlled and played the anechoic sound in the system, allowing respondents to listen to design scenarios, providing a better foundation for decision making with respect to room acoustics.

Multiple informal experience tests in VR with Auralization revealed that the ability to combine experiencing visual and audibly realistic visualisations gave a more tangible basis for selection of acoustic design solutions, than the calculations made and presented in writing or through 3D models.

Real-time evaluation of room acoustic is feasible through use of the Virtual Reality with Auralization system presented in this paper, using IFC-based Virtual Reality and Auralization engines. Further research is, however needed, regarding use of the system in multiple companies, in order to conclude finally on the systems' accuracy and realism.

## 6 Acknowledgement

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# CONVERTING BRAZILIAN ACCESSIBILITY STANDARD FOR BIM-BASED CODE CHECKING USING RASE AND SMC

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**Abstract:** The Architecture, Engineering and Construction (AEC) industry is regulated by a high number of rules given by laws, codes and standards, at national and international level. Much effort has been made to automate the checking of these rules, which is increasingly more efficient in terms of time and cost, such as the use of BIM tools. However, regulatory standards are written in human language. Wide and complex, they require substantial understanding and knowledge on the part of users. To allow the automation of the verification, it is first necessary a semantic analysis of the normative text, in order to adapt its meaning to a language that can be interpreted by computer software. This article demonstrates the application of the RASE methodology of semantic mark-up within the Brazilian accessibility standard, the configuration of Solibri Model Checker rules from these logical statements obtained and a simulation of these rules checking in a BIM model prepared for this purpose. The results were quantified for this paper and proved to be promising. They also identified the need for research to change the methodology of how the rules should be written so that they can be interpreted computationally.

**Keywords:** Code checking, RASE, Accessibility, BIM.

## 1 INTRODUCTION

Every project for Architecture, Engineering and Construction (AEC), whatever its size, needs to fulfil a series of requirements. The client's own needs program is one of them, which will vary from project to project. But there are sets of requirements that are repeated for different projects, such as the Constructions Codes and Accessibility Standards, for example. In these sets there are prescriptive requirements, more related to quantity, and performance requirements, which are also related to quality.

Verification of compliance with these requirements, made by a human, for a given project, requires long periods and is subject to the analyst's capabilities and the quality of the project's graphic representation, among other variables. This process, in addition to being time consuming, is highly susceptible to errors, omissions and lack of standardization.

In Computer Science, Model Checking refers to the test performed on a model to verify that it meets certain specifications. The use of a computational tool that performs this verification in BIM projects automatically explores two great potentials of the methodology: agility and reliability. However, there is an arduous task that precedes this automation. According to the process proposed by Eastman, et al. (2009), there are 4

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stages of computer rule checking: (i) interpretation and structuring, that is, conversion of rules to computational language; (ii) preparation of the BIM model so that it can be correctly interpreted by the verification software; (iii) execution of the rule; and (iv) communication, a stage in which results are presented, which may still need human actions depending on their classification.

The present work, despite going through the four phases of Eastman, et al. (2009) will focus on the first two: rule interpretation and structuring them, and preparation of the BIM model. The following steps (execute and communicate) will be carried out in order to quantify the results. This paper is part of an ongoing research that aims to convert part of the Brazilian accessibility standards into testable logical statements, using the RASE methodology proposed by Hjelseth and Nisbet (2011). These statements will serve as a basis for configuring a commercial rule checking software, Solibri Model Checker, or SMC, in order to quantify and critically analyse its results. In order to achieve this objective, an existing building BIM prototype was developed, whose project had already been subjected to human verification of compliance with ABNT NBR 9050.

## 2 Literature Review

Many efforts have been made in the application of automatic rule checking. According to Dimyadi and Amor (2013), the idea of automating the process of checking compliance with code requirements has been explored since the 1960s. Some expressive cases reported by Eastman, et al. (2009) started in 1995 with CORENET Singapore, started with CAD drawings (Khemlani, 2005). Eastman, et al. (2009) still cite Norwegian Statsbygg's, the Cooperative Research Centre for Construction Innovation in Australia, the International Code Council (ICC), and the General Service Administration (GSA), both in the USA. Since then, there have been several approaches on the topic, however, until the early 2010s, few have evolved into a practical solution (Manzione, 2019).

From the last decade, however, there has been an increase in the number of searches. The dissemination of BIM tools certainly contributed to this, but the results showed that the process prior to the verification itself is essential and as arduous as predicted by Eastman, et al. (2009). Among the four steps proposed by the authors, the first step, of rules interpretation and conversion to a computational logic language, has been little explored.

The current building codes are a collection of many years of constructive experience, trials, errors and a series of accidents. For this reason, they are highly complex and quite extensive (Solihin, 2015). According to Hjelseth (2012), the regulations are written in legal / technical language for interpretation by a qualified professional. For the implementation in model verification software, the regulations must often be restructured to give a more applicable structure.

Some recent and recognized case studies have obtained results that reinforce the need for more research in this subject. Mainardi Neto (2016) simulated the application of Metrô (São Paulo’s Subway Company) rules document and concluded that one of the most critical points in the automation in code checking is the translation of an existing rule into an applicable rule in a software for this use. Rodrigues (2015) carried out a similar survey on Portugal's Accessibility Code and pointed out that the way the regulation is drafted influences automatic verification and found that only about 38% of the requirements could be verified directly. Getuli et al. (2017) conducted research focused on systems interoperability for rule checking in Italy and highlight the importance of structuring the rules.

Hjelseth and Nisbet (2010) deepened the study to this issue. According to them, we see from the history of AI (artificial intelligence) and KBE (knowledge-based engineering) and KM (knowledge management) that capturing information in a meaningful and reliable way has not been a direct process. The relevant information in these documents need to be captured as rules for model checking in a time and cost effective way. Two procedures developed by these authors help capturing and converting that information. First, the T3-concept sort out data based on classification of regulations in three main type of methods for design rules: Translate, Transform and Transfer. Then, RASE methodology uses mark-up based on the four operators: requirement (R), applicabilities (A), selection (S) and exceptions (E) on normative text. It is a concept based on semantics for transforming normative documents into simple and well-defined rules that can be implemented in model verification software based on BIM / IFC. To confirm the accuracy of the process Hjelseth and Nisbet (2011), in one case study, re-transformed the logical statement back into prose, successfully.

According to Manzione (2019) it is a problem that will demand innovative solutions, aiming to improve the state of the art of regulatory knowledge, while also allowing other domains, such as the legal one, to develop its rules directly in a computational format. This paradigm shift will alter the current, paper-based standard, which requires human interpretive effort, towards the electronic, precise, controllable and reliable standard. The legal and normative databases may, in the future, have, through interoperability, a direct link to the modelling and content search software, through the Internet.

## 3 METHODOLOGY

This work will follow the Design Science Research (DSR) methodology, according to the methods proposed by Dresch, et al. (2015), through which the problem will be properly studied and understood, the existing artefacts will be researched while carrying out a systematic review of the literature on the theme and a solution to the problem will be proposed, describing the weaknesses and potentialities of the process.

In this paper, the survey of accessibility rules will be restricted to Section 6 of ABNT NBR 9050:2015. The data obtained will be quantified and presented graphically. The general conclusion will seek to identify the strengths and weaknesses, difficulties and needs to improve the process, be it in the elaboration of rules, BIM modelling and automatic verification scheme.

In summary, the work is structured to answer the questions on Figure 1.

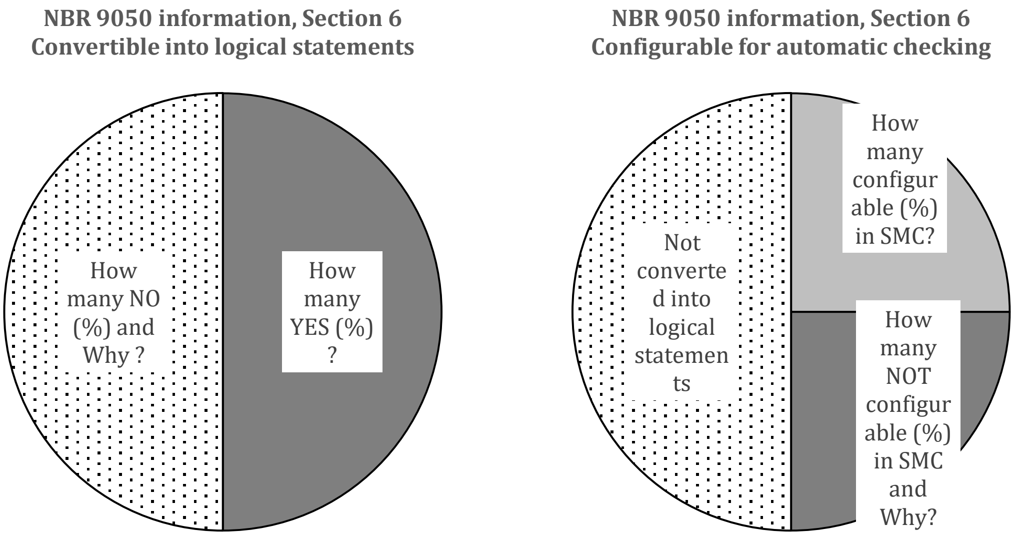


Figure 1: Questions to be answered

## 4 Experiment and Results

This research topic is ordered according to the 4 steps of the automatic rules verification process proposed by Eastman, et al. (2009) with a small adaptation of the last two, in order to deepen the description of the rule execution (third step), and reduce the reporting phase of the software results (fourth step).

The first stage (item 4.1) aims at the interpretation and structuring of the rules. The basic text is Section 6 of NBR 9050, entitled Accesses and Circulation. The second stage (item 4.2) is the preparation of the BIM model of a real building (Figure 2). This is the Professor Cândido de Oliveira public school in São Paulo, which was the subject of a contract with the Foundation for the Development of Education (FDE) for the development of executive projects to adapt the building to accessibility, throughout 2018. The original building was built in 1977, prior to the publication of the first edition of the NBR 9050 standard, dated 1985. That contract with FDE required full compliance with the third edition of the standard, of 2015, currently in force. Thus, the solutions proposed in the project fully considered what the standard under study requires.

It should be noted that this contract was carried out in the "conventional" way of design, coordination and inspection, that is, with the development of the project in CAD software, analysis of "2D" drawings (Plans, Sections, Elevations and Details) and comments made on drawing boards, in addition to visual verification of compliance with design requirements. The project was approved by the FDE, which shows that its solutions have been validated by qualified professionals and that its elements meet the requirements of NBR 9050:2015.

The third stage proposed by Eastman, et al. (2009) is the execution of the rule. Item 4.3 will deepen the description of the SMC configuration process to check the statements produced in step 1 in the model developed in step 2.

The fourth stage is communication, that is, how the software “reports” the occurrences to the user, which can demand new actions according to the result. In this work, item 4.4 will present quantitatively the results of the verification performed in step 3. This will allow to graphically observe which portion of NBR 9050 could be verified in the process.

Figure 2: BIM Model of the real building (Source: author; ArchiCAD screen)

## 4.1 Step 1 - Conversion of the normative text

This step consists of applying the T3 concept over the text of Section 6 of NBR 9050 and applying the RASE methodology on items classified as T1 and T2.

**T3 Concept**. This topic presents and quantifies the results of the T3 concept applied to the text of Section 6 of NBR 9050 "*Accesses and Circulation*", composed of 15 sub-items. Its content is written in prose, with numbered paragraphs, including tables and figures. Of the 15 sub-items, 3 were excluded from the scope of this research because they did not apply to the building under study: 6.10 "*Electromechanical circulation equipment*", 6.12 "*External circulation*" and 6.13 "*Pedestrian walkway*". The remaining 12 sub-items were transcribed to an Excel spreadsheet, with each paragraph occupying a cell. Each cell was interpreted and classified as recommended by T3:

- T1 (translate): normative text with clear metrics, which can be directly submitted to RASE marking;
- T2 (transform): the text needs to be reformulated based on its intentions, so that it is submitted to RASE from the reformulation;
- T3 (transfer): the text contains generic statements, with subjective metrics or even without clear metrics that, in order to be met, need to be assessed "manually", whose decision must be made by a specialist, that is, not subject to automatic verification.

Outside the written text, relevant and measurable information was found in 29 figures and 3 tables, consequently indispensable for the RASE marking. This information was transformed into simple sentences with measurable metrics, therefore classified as T2.

Conversely, redundant stretches were perceived with other parts of the Standard itself, as well as definitions and explanatory notes, all without direct relevance to the RASE marking, necessary only for the understanding of the adjacent elements. They were classified as:

- Redundant: content that is repeated in some part of the Standard with the same objective;

- Definitions: content not applicable because it presents definitions, justifications or explanatory notes, necessary only for the general understanding of the text, without implying recommendations or metrics;

Some sentences in the original text needed to be subdivided into smaller sentences that resulted in different classifications. For example, item 6.11.2.6 "*Doors must be able to be opened with a single movement, and their handles must be of the lever type, installed at a height between 0.80 m and 1.10 m (... )*" can be rewritten in two sentences: "Doors must be able to be opened with a single movement" and "door handles must be of the lever type, installed at a height between 0.80 m and 1.10 m". In this case, the first sentence was classified as T3, given the non-measurable character of the act of opening the door and the second sentence was classified as T1, as it contains a clear subject and predicate, with well-defined metrics.

Examples of the classification applied to the text:

T1 (translate): item 6.6.4.1 "*When there is a door on the landing, its sweep area cannot interfere with the minimum dimension of the landing.*" Its interpretation results in a logical statement of simple verification: there is an application (doors on the landing) and a requirement (do not advance on the minimum threshold size).

T2 (transform): most of the T2 items need only restructuring in order to result in minor logical statements. Item 6.3.3 consists of a paragraph with several sentences. Its content can be rewritten with simple logical statements as shown in Table 1.

Table 1: Restructuring item 6.3.3 of NBR 9050.

| Original text | Text rewritten in logical statements |
|---|---|
| The transverse slope of the surface must be up to 2% for indoor floors and up to 3% for outdoor floors. The longitudinal slope of the surface must be less than 5%. Slopes equal to or greater than 5% are considered ramps and, therefore, must meet 6.6. | Internal floors must have a transversal inclination less than or equal to 2%. |
| | External floors must have a transversal inclination less than or equal to 3%. |
| | Internal and external floors must have a longitudinal slope of less than 5%. |
| | Floors with a longitudinal slope greater than or equal to 5% are considered ramps must meet 6.6. |

As for item 6.6.2.6, it presents its information through a figure: "*Every ramp must have a handrail of two heights on each side, as shown in Figure 72*". Figure 72 of the Standard is reproduced in Figure 3.

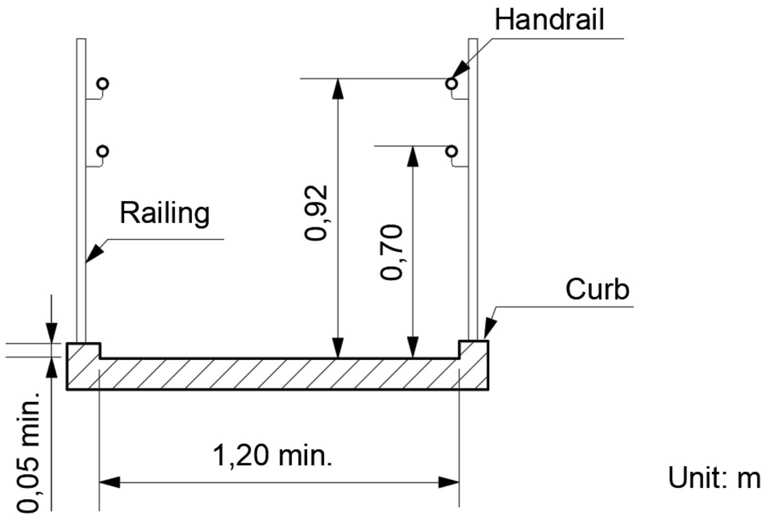


Figure 3: Figure 72 from NBR 9050 (Source: adapted from ABNT (2015))

Measurable data were taken from the figure and rewritten as a clause classified as T2: "ramps handrails must be 70 cm and 92 cm high". It is important to note that this item would be redundant with 6.9.2.1, subitem of "*Handrails and guardrails*", but it appears here as a ramp requirement (having a handrail).

T3 (transfer): according to item 6.9.1, handrails "*must be firmly fixed to the walls or to the support bars, ensuring safe conditions of use (...)*". How to measure or quantify "safe conditions of use"? Should be transferred for manual evaluation by a specialist.

Redundant: The term "*when installed in sports venues, doors must have a minimum clearance of 1.00 m*" appears in items 6.11.2.4 and 6.11.2.12. In the first occurrence it was rewritten (T2) and in the second it was classified as redundant.

Definitions: item 6.6.2 "*To ensure that a ramp is accessible, the maximum slope limits, the unevenness to be overcome and the maximum number of segments are defined*". There are no parameters applicable to the verification, which appear in the continuation of the item.

Thus, excluding titles, subtitles and items outside the scope, the classifications above resulted in 232 (two hundred and thirty-two) information, distributed as in Table 2. It is noteworthy that less than 10% of the analysed content contains clear metrics (T1), allowing conversion to computational language only using the RASE operators. Items of the Standard that could be classified as T1, given the presence of clear metrics, but written in more than one sentence (phrase), were classified in this work as T2 (transform), because according to Hjelseth and Nisbet (2011) the intention of explicitly using the source text transformation is to expand the number of rules that can be extracted from the original text.

Positive fact is that more than 3/4 of the content (sum of T1 and T2, or 175 items) can be submitted to RASE marking for conversion into testable logical statements, as discussed in the next topic.

Another important data for the research is the "total requirements". Excluding redundant definitions and phrases, it is the sum of T1, T2 and T3, equal to 211. This value expresses the number of requirements identified in this part of the Standard, regardless of its understanding. It will serve as a comparison with the results sought.

Table 2: Information extracted from the normative text (T3 concept).

| Identification | Occurrences | Percentage |
|---|---|---|
| T1 (translate) | 22 | 9,5% |
| T2 (transform) | 153 | 65,9% |
| T3 (transfer) | 36 | 15,5% |
| Redundant | 6 | 2,6% |
| Definitions | 15 | 6,5% |
| **TOTAL** | **232** | **100,0%** |

**RASE Methodology**. RASE consists of identifying, in each statement, the four logical operators: requirement (R); applicability (A); selection (S); and exception (E). The 175 (one hundred and seventy-five) logical statements resulting from T3 will be submitted to RASE marking.

According to Hjelseth and Nisbet (2011), the most obvious and easily identified are ‘requirements’, as they are usually associated with the imperative “must” or “shall”. In the statement “*route between vehicle parking and access must make up an accessible route*”, the requirement is ‘make up an accessible route’.

Then there will always be a term that identifies to whom or to whom the requirement applies. In the previous example, ‘applicability’ is ‘the path between vehicle parking and accesses’.

Eventually the text will present a 'selection' of this applicability, something like a subset when it splits. For example, “*for curved ramps, the maximum allowable inclination is 8.33%*”: we have ‘ramps’ as an application and ‘curved’ as a ‘selection’ of the ramp type.

‘Exception’ concept can be as simple as “*ramps mentioned in 10.4 (audience and stages) except for this requirement*”: just exclude audience and stage ramps from the requirement applied to this rule. Or more complex as “*every accessible route must be provided with natural or artificial lighting with a minimum illuminance level of 150 lux (...). Lower levels of illuminance are accepted for specific environments, such as cinemas (...)*”. Here, the second sentence presents an exception to the first: ‘environments, except cinemas, must be provided with lighting with a minimum illuminance level of 150 lux’.

Hjelseth and Nisbet (2011) point out that the sentences marked with the four operators, requirement (R), applicability (A), selection (S) and exception (E), will contain metric phrases, to which an object, a property, a comparator and a target value can be systematically assigned. The object and property should ideally be elaborated from terms classified by standardized systems. In this work they will be transcribed directly from the terms of the accessibility standard, aiming whenever possible to match the terms that will be used in the model. The target value can be numeric, with any unit, for which the comparator will be "equal", "less than", "greater than" or its variants. If the target value is descriptive, the only relevant comparators will be "equal" or "different". If it still refers to a group of elements, comparators can be "include" or "exclude" for any element in the group.

The following example shows the conversion of item 6.6.2.4 from its original text to logical statements.

- Original text: "*Cross slope cannot exceed 2% on internal ramps and 3% on external ramps.*"

Text converted into logical statements:

- Cross slope [R] of internal [S] ramps [A] cannot exceed 2% [R];
- Cross slope [R] of external [S] ramps [A] cannot exceed 3% [R].

Table 3 shows the attribution of objects, properties and values to the respective metric phrases.

Table 3: Metric phrases with assigned objects, properties and values.

| Metric phrase | Type (RASE) | Object | Property | Comparator | Target value | Unit |
|---|---|---|---|---|---|---|
| Ramp | Applicability | Element | Type | Includes | ramp | |
| Internal | Selection | Localization | Internal | = | TRUE | |
| maximum cross slope 2% | Requirement | Ramp | Cross slope | ≤ | 2 | % |
| Ramp | Applicability | Element | Type | Includes | ramp | |
| External | Selection | Localization | Internal | = | FALSE | |
| maximum cross slope 3% | Requirement | Ramp | Cross slope | ≤ | 3 | % |

After the assignment of objects, properties, comparators and targets to the logical statements resulting from the previous step (T3 concept), a spreadsheet was built with all the data obtained by RASE. These data will be used to feed SMC, a process described in step 3 of setting the rules.

In this spreadsheet, each of the 175 requirements was also marked with "YES" or "NO", depending on its possibility of application to the model under study. Those that are not applicable can refer to elements that do not exist in the real building (curved ramp, for example), or not modelled in the Architecture discipline (visual communication, i.e.). The obtained result showed that 79 requirements (45%) are applicable to the prototype, against 96 not applicable (55%).

## 4.2 Step 2 - Model Preparation

For the rule-checking software to read the model correctly, it must meet certain requirements. For example, for the verification of the inclination of a ramp to be possible, it must be read as such, and not as a tile. According to Eastman, et al. (2009), there must be shared conventions in relation to the coded rules so that they correspond to the properties and structures incorporated in the construction model.

In order to resolve this, among many other issues, there are classification systems. This research sought to adopt the recommendations of ABNT NBR 15.965 "*Construction information classification system*", based on the OmniClass (or OCCS) classification proposed by the CSI (Construction Specifications Institute, Inc.). The modeling software used (ArchiCAD, version 22) presents this applicable classification system as a simple attribute of the element. In addition to be an international classification recommendation, aiming at the use of this work in other countries.

Within the model, 'Zone' is a spatial delimitation, with its own properties (Figure 4). In addition to the classification, in order to allow accessibility verification, it is necessary to inform additional properties of the Zone in the modelling software. In ArchiCAD, in the same classification window we can enter the following parameters, which will be input data in the verification software:

- renovation status: existing, to be demolished or to be built;
- openings: emergency exit (true or false) and accessible (ditto);
- floor: non-skid (true or false);
- property: private, rented, shared or public;
- lighting level: numerical value expressed in lux;

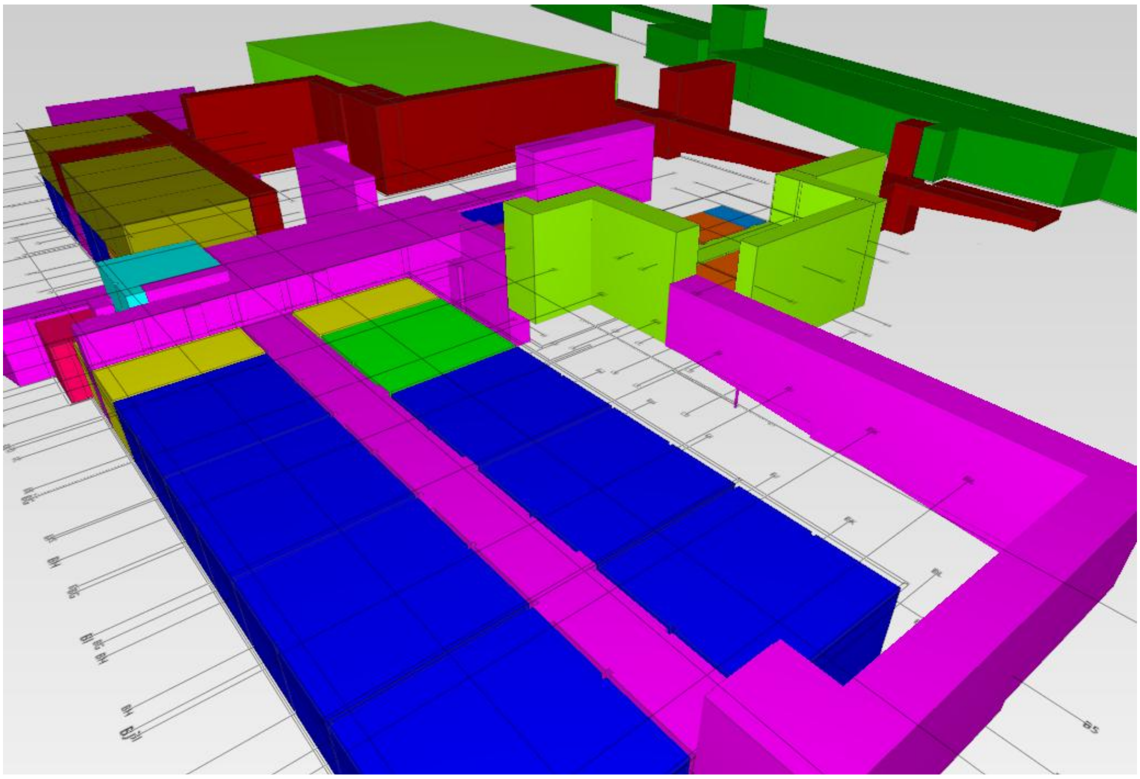

Figure 4: Model Zones (Source: author; SMC screen)

If not configured, the above parameters would be identified as 'undefined' in the model. This would not prevent the verification of rules, but they should be correctly filtered in the verification software to obtain reliable results.

During the tests carried out, it was also noticed the need to add a specific configuration in the zone's *IfcIdentifier* so that the Accessible Route of the model is identified, within the group of properties *PSet_SpaceCommon*. The simple marking that the opening is accessible does not define a Zone as an Accessible Route. As the definition of this property is descriptive, in this work the term "accessible route" was adopted for the spaces that make up this route.

In addition to the Zones, the correct reading of the model by the verification software also depends on the classification of the elements (ramps, stairs, guardrails, etc.). The first tests revealed that an “L” ramp will not be recognized in this way just by classifying the Zone that surrounds it as ‘ramp’. The stretch of two flights shown in Figure 5 was modelled with independent elements: flights, landing, guardrails and curbs, and around it was defined its Zone involving all these elements. This was not enough for SMC to consider this set as a single ramp, nor its level as an inter-daily level (which is subject to specific rules, different from the start and end levels).

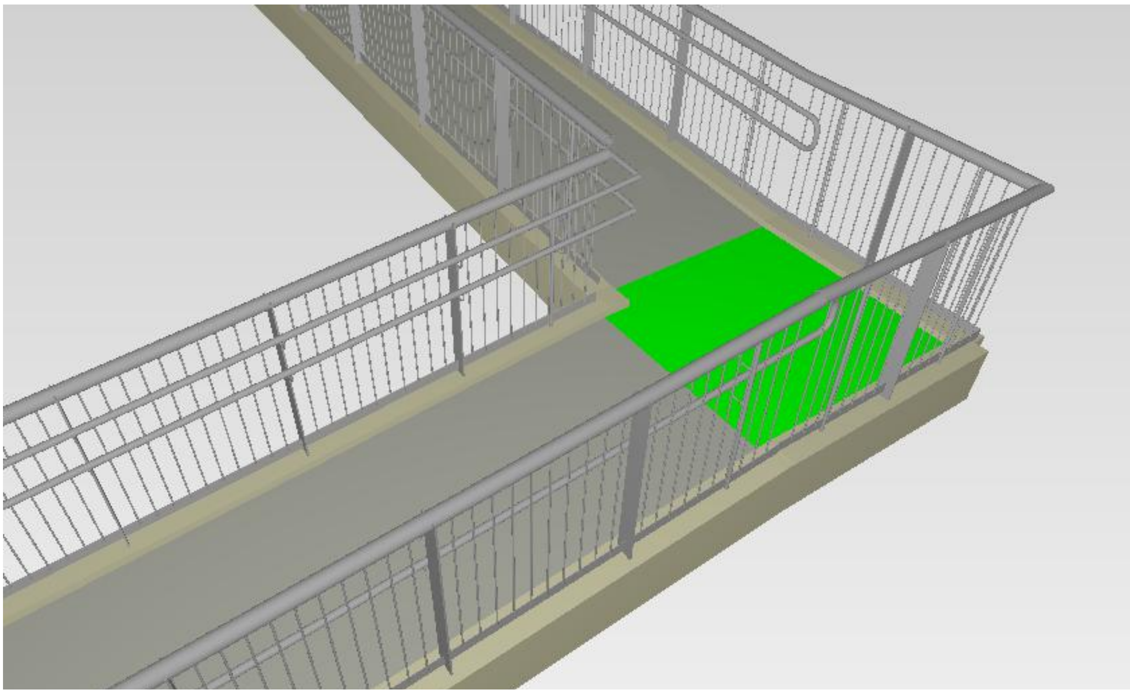

Figure 5: "L" ramp with intermediate landing selected (Source: author; SMC screen)

These properties are not usually reported in a model at the design phases. As well observed by Eastman, et al. (2009), the models created so far do not normally include the level of detail needed for construction codes or other types of rules verification. When including them, however, it is convenient that they go along with the configuration of the rules.

Thus, in this work, all components of a ramp, necessary to comply with NBR 9050 will be classified by the code OmniClass 21-02 10 10 50 Ramps.

Finally, in order to efficiently exchange the model file with other software (SMC, i.e.), the format used was the IFC (Industry Foundation Classes). This format guarantees, according to tests carried out during the research, that the OmniClass classification of spaces and elements is preserved in the export and import processes.

## 4.3 Step 3 - Setting the rules

This step’s aim is, from the table of metric phrases produced in Step 1 - Conversion of the normative text, to configure the rules verification software. To expose the logical structure created when applying RASE statements (requirement, applicability, selection or exception), this work produced some flowcharts. The example below (Figure 6) is part of the flowchart created for the ‘floor’ object. The complete flowchart is not only the sequence of decisions of an item of the Standard, but the combination of all the requirements applicable to that object. In another Brazilian research, Andrade and Silva (2017) realizes that efforts to link the requirements of the standard to the SMC check were not carried out directly, that is, on average, more than 4 software rules to verify a single requirement of the standard.

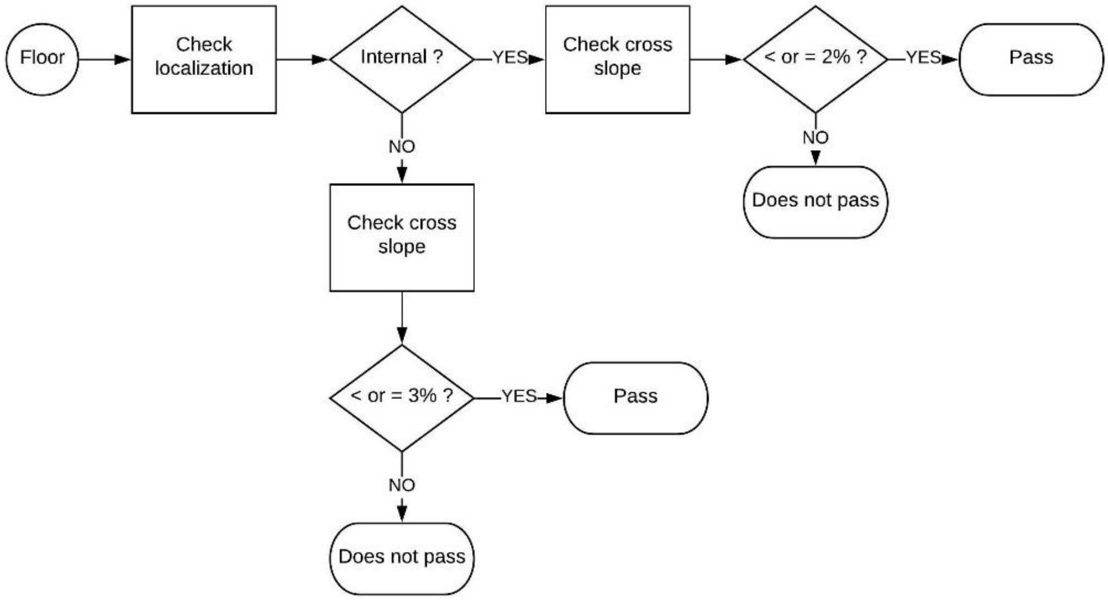


Figure 6: Part of the decision flowchart for the ‘floor’ object (Source: author)

The dynamics of the verification, in a very simplified way, can be described as the comparison between the properties of a model object and the rule parameters, the results of which can be "pass" (totally or partially) or "does not pass". For this, the rule parameters must consider the model classifications. An example is the SMC rule #132 *Space Area*: it checks whether the areas of certain spaces are within a specific range of values, configured by the user. For that, it will search for the spaces determined in her filter, check the ‘area’ property of that space and compare the values. There are more complex rules that check interference between components, connections between spaces, rates, proportions, etc., but it will always depend on the correct configuration of the filters and parameters.

It is also possible to combine more than one rule (its repetition or a different rule) to achieve a certain objective. One of the functions of this combination is called *Gatekeeper*. Nesting one rule under another will cause the bottom rule to be checked only if a certain condition of the top rule is passed. This allows combining rules to comply with the decision sequence assembled in the flowchart. Thus, the Rulesets will result from the Flowcharts, which in turn originated from the RASE methodology.

An example of this combination is the distinction between 'isolated step' and ‘stair’. The modelling software creates these two objects with the same tool, and both are likely to receive the same classification, but the accessibility standard has different requirements to them. In NBR 9050, only the sequence of three risers or more will be considered a stair. Figure 7 shows the fulfilment of the following condition: how many risers are there in an object 'stair'? If the answer is greater than or equal ‘3’, the object will be driven to 'stair' rule checking defined in the Standard. Otherwise, the object goes to the 'isolated steps' checking.

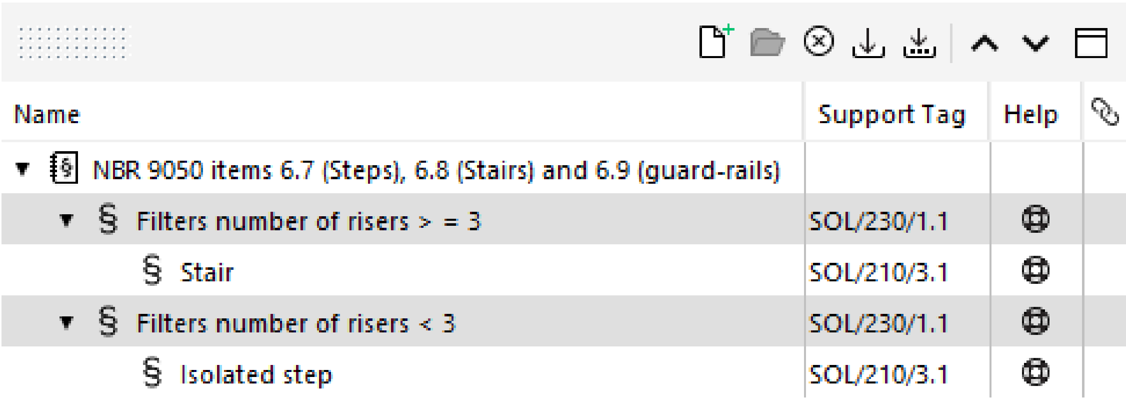


Figure 7: Nested rules (Source: author; SMC screen)

Besides that, rules can be configured to request some action from the user before their execution. This can be used when the choice between flowchart paths de-pends on properties not fed into the model, that is, it will not result from the comparison between similar objects. For example, there are requirements for residential buildings that do not apply to public buildings. If this property (building usage) is not part of the model, as it is not characteristic of a specific object, the rule will ask the user for a task to specify the building usage. These tasks will be shown in the SMC To Do View.

In the checking communication, SMC gathers the events according to their level of severity, between high, medium or low. These levels can be configured according to minimum and maximum limits established by the user. In this research, these levels were not adjusted, since its main objective is to assess how much is subject to automation, regardless of the type of non-compliance with Standard.

## 4.4 Step 4 – Presenting Checking results

In order to answer the question above, the same spreadsheet built for RASE was fed with an additional column, whose content is: Was the requirement possible or not to be configured for SMC Checking? The total number of YES responses will be the comparative data with the number of “automated” requirements in Section 6 of NBR 9050 (the sum of statements T1 and T2 from step 1). It will also be compared with the “total rules” in Section 6, including texts classified as T3. Figure 8 shows the Checking and Results Summary Views of SMC.

To determine whether or not a requirement could be configured in SMC, several simulations were performed. The elements that were not verified due to some deficiency of the model were classified as YES, since their automation proved to be possible. Obviously, the results of rules that “did not pass” were also classified as YES, since the objective is not to ratify the model's compliance with the Standard.

It was also noted YES for rules that can be verified in the way that the Standard describes it, even though it refers to external links. Example: an exception in item 6.1.1.1 was rewritten as “*lower levels of illuminance are accepted for specific environments, such as cinemas, theatres or others, according to specific technical standards*”. Solibri will exclude the verification illuminance level of these environments, and it can be pointed out that this environment needs an action from the verifier, even if the “specific technical standards” are not configured for verification.

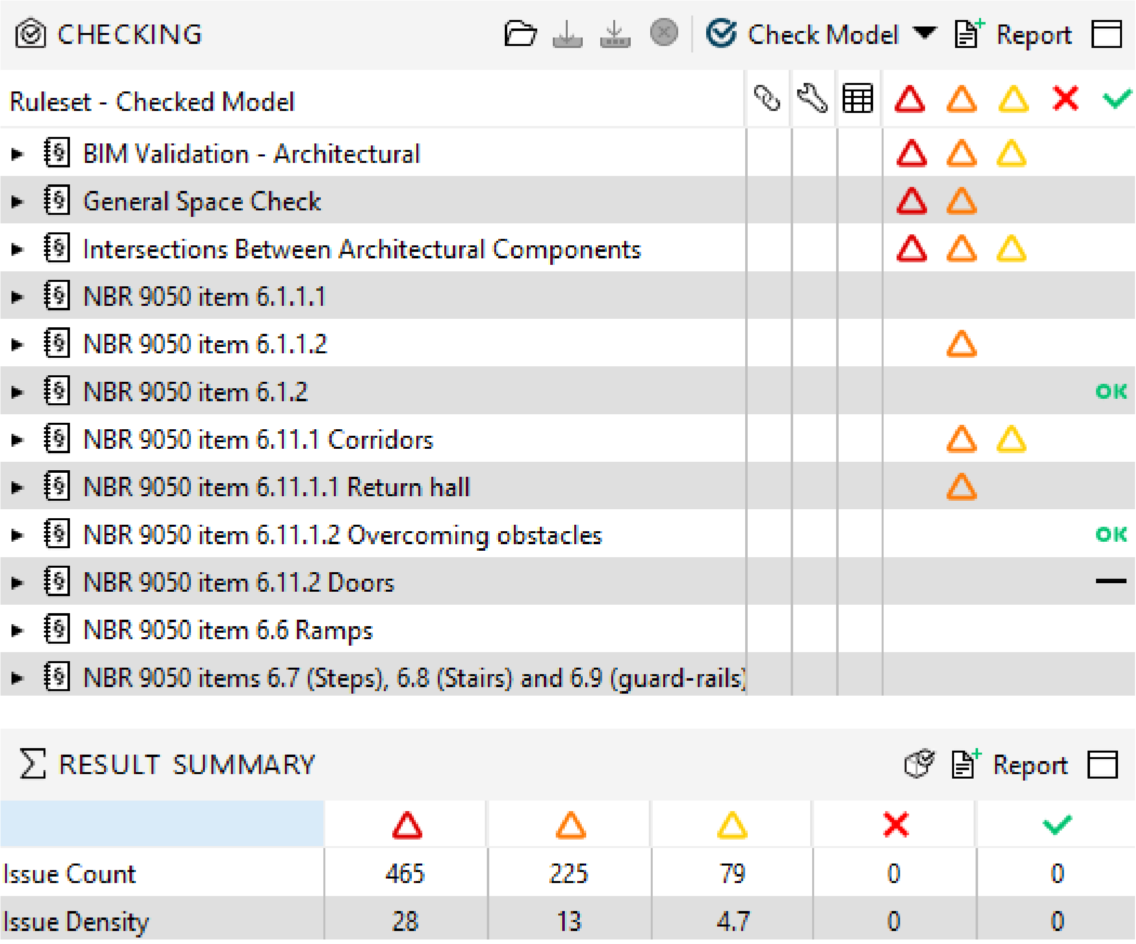


Figure 8: Reported results (Source: author; SMC screen)

Likewise, possible rules for verification by the software, despite the need for an extra action by the verifier, were classified as YES. Example: one of the logical statements in item 6.2.2 is "*the main building entrance, or the entrance for the largest number of people, has the obligation to meet all accessibility conditions.*" It is likely that the model does not contain the information that an entry, not being the main one, is the access of the largest number of people. In this case, a task prior to the rule's execution must require the verifier to inform the expected number of people for all entries.

Situations in which the Standard determines, for a certain parameter, a minimum value and another recommended value, were classified as YES, however the recommended value was ignored. In the case of "*the width for ramps on accessible routes must be at least 1.20 m, and 1.50 m recommended*", a rule was created to check compliance with the minimum value (1.20 m).

Requirements that could not feed any Solibri rule were classified as NO. For example, the statement "*handrails must be 70 cm and 92 cm high*" could not be verified. Solibri can check if the handrail height is within a certain range, but not a double handrail (two heights).

There were original phrases, broken down into two logical statements, whose classifications were NO for the first and YES for the second. Item 6.2.7 says that "*revolving doors should be avoided, but when they are installed (...) another entrance should be provided, which guarantees accessibility conditions*". The software will not be able to check whether the choice of a revolving door could have been avoided, but whether there is another accessible entry associated with it.

Simple sentences, but with subjective conditions were classified as NO. According to item 6.6.2.2, "*in renovations, when the possibilities of solutions that fully meet Table 6 are exhausted, inclinations greater than 8.33% can be used (...)*". The "exhaustion" of possibilities cannot be verified automatically. The same goes for expressions like "*as long as technically justified*" and similar.

From the quantitative premises described, the results obtained are as follows, graphically represented in Figure 9:

- Amount of information (including Redundant and Definitions) = 232 (100%);
- Total requirements (T1 + T2 + T3) = 211 (90.9%);
- Logical statements (T1 + T2) = 175 (75.4%);

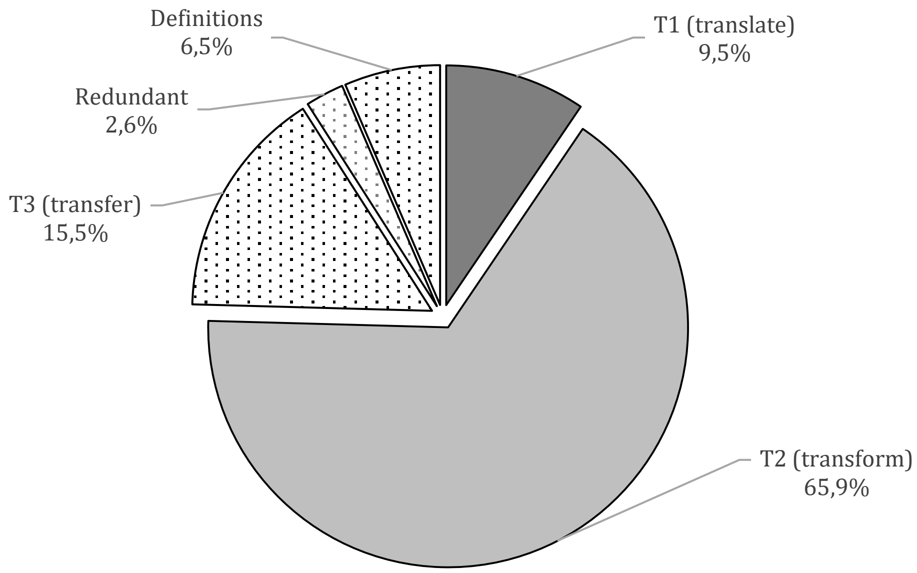


Figure 9: NBR 9050 - Distribution of NBR 9050 Section 6 information according to T3

Of these data, work showed that 108 requirements (46.5% of total requirements or 61.7% of logical statements) are possible to check in SMC. Figure 10 shows how the questions raised in Figure 1 were answered.

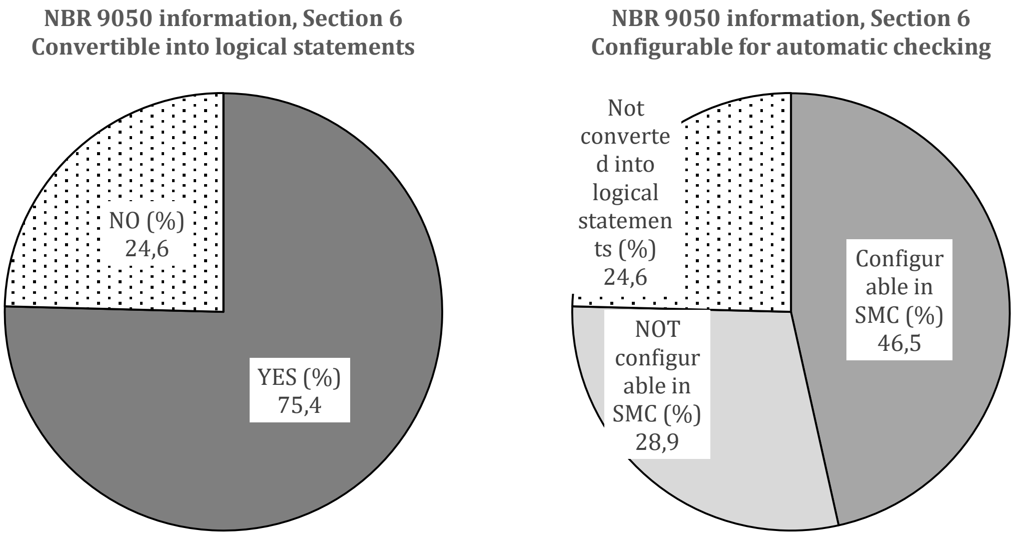


Figure 10: Research results

## 5 Conclusions

This paper submitted a section of the Brazilian accessibility code to T3 and RASE methodologies and delineated a set of rules in Solibri Model Checker, based on the resulted statements from the process. For this purpose, data within the Standard was quantified and results showed that almost half of that information was able to be checked in SMC and one third part could be converted into formal logic but was not able to be checked, due to software limitations. It also identified how much could not be converted into formal logic and why. This approach can be a systematic way to assessment of code provisions.

The application of T3 and RASE methodologies to the regulatory text revealed issues to be observed when it is intended to prepare it for BIM code checking. These questions mainly refer to deficiencies present in the way it is written. There are intentionally subjective requirements in the standard, like performance-based prescriptions, which gives the designer a desirable freedom. However, even for the technical aspects and quantitative items, the description through prose text, in a language written by and for humans, does not support automation. Even the association with figures, which is intended to facilitate the user's understanding, requires a logical structure for automatic checking.

Standard text should ideally be drawn from terms classified by standardized classification systems (e.g. OmniClass), so that the rule property and the model object are compatible. Likewise, designers must adopt standardized classifications and create a routine of feeding the model with the necessary information during the design process. Verification software alone will not perform its potential if these methodologies are not applied first. The strength of this process relies on the connection between text (codes) and the software (technology), provided by RASE (methodology).

Future researches could focus on evolving normative writing, like a text editor based on RASE, which would inform the legislator of the lack of any logical data. For modelling, developers can incorporate verification tools in their software. The creation of new checking software will be beneficial for the evolution of the systems.

## 6 Acknowledgments

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# SEMANTIC ENRICHMENT OF ASSOCIATION RULES DISCOVERED IN OPERATIONAL BUILDING DATA

**Ekaterina Petrova[1] and Pieter Pauwels[2]**

**Abstract:** The advancements in Building Information Modelling, Building Monitoring Systems and machine learning have made the discovery of hidden insights and performance patterns in operational building data possible and highly accurate. Semantic web technologies play a fundamental role in terms of knowledge representation and provide the necessary infrastructure for reuse of the discovered insights. Such knowledge can be of particular importance to decision-making for building performance improvement, however, this requires patterns discovered with traditional data mining techniques to be attributed with semantics, so that they can be machine-interpretable and reusable. Using linked data-based crowdsourcing techniques for interpretation of building performance patterns enables the creation of knowledge graphs of building data, enriched with contextualized building performance insights. This paper presents a crowdsourcing mechanism that allows the semantic enrichment of building performance patterns through semantic annotation and classification. We discuss the results and the potential of linked building data graphs enriched with building performance insights.

**Keywords:** Semantics, Association Rule Mining, semantic data mining, linked data, building performance, crowdsourcing.

## 1 INTRODUCTION

With the emergence and establishment of Building Information Modelling (Borrmann et al. 2018; Sacks et al. 2018) the Architecture, Engineering and Construction (AEC) industry underwent a paradigm shift in the creation and use of information. The exponential generation of data throughout the building lifecycle and the advances in analytical approaches have augmented that shift even more by giving AEC practices the ability to make use of and reuse data in a structured way. Moreover, being able to discover valuable insights in the data (e.g. building data, simulation data, IoT data, etc.) makes it possible to cater to high-level decision making related to sustainability, energy efficiency, indoor environmental quality, occupant comfort, etc. (Fan et al. 2018a). Advanced knowledge discovery methods aid the extraction of high-level knowledge from low-level data (Fayyad et al. 1996). Such knowledge allows higher level analyses and has the potential to redefine the way buildings are designed by serving as an evidence base in performance-oriented design decision-making (Petrova et al. 2019).

However, to be useful and have an impact on decision-making, the insights discovered in data need to be transformed into actionable knowledge, which includes analytical efforts that require a lot more than identifying an analytical goal and selecting appropriate data mining algorithms (Fayyad et al. 1996). Crucial to knowledge discovery

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are the interpretation, contextualization, and enabling the reuse of building performance insights. Meaning is not explicit in insights discovered by data mining algorithms. Therefore, it needs to be attributed through semantic classification and annotation by domain experts, who can assess the value and meaning of the discovered building performance insights (e.g. frequent patterns, anomalies, association and sequential rules, etc.). Furthermore, to close the holistic information management cycle and enable reuse, the discovered knowledge has to be machine-readable and implementable in knowledge-based (decision support) systems.

In this regard, a reconciliation of statistical and symbolic Artificial Intelligence (AI) can provide the necessary combination of approaches to facilitate the above-mentioned objectives. Statistical methods have proven to be useful for discovering patterns, regularities or irregularities in data and symbolic representations excel at capturing the knowledge within a given domain explicitly, thereby allowing various forms of inference (Hoehndorf and Queralt-Rosinach 2017). As part of the statistical realm, machine learning approaches for knowledge discovery allow the extraction of valuable insights from the large datasets generated throughout the entire building life cycle. Semantic data modelling, linked data and web technologies (Berners-Lee et al. 2001; Bizer et al. 2009), on the other hand, have made it possible to represent the built environment formally, retrieve knowledge according to domain-specific requirements and reason about building performance (El-Diraby 2013; Pauwels et al. 2017).

Due to their proven ability to support decision-making, both approaches have independently received major attention in AEC. In depth research has been performed to identify how to transform raw data into building performance insights and make use of the multiplicity of collected, but usually rarely reused data. Included here are efforts aiming to define the various building data types (Petrova et al. 2019), as well as corresponding machine learning methods for data pre-processing, mining, visualization and use of discovered knowledge (Fan et al. 2015; Fan et al. 2018a; Fan et al. 2018b; Miller et al. 2018; D'Oca et al. 2018; Fan et al. 2019). Research has also shown that publishing data effectively, breaking up information silos, integration of data across domains and making data readable and understandable by both machines and humans is equally important. The latter is showcased at length in state of the art research contributions related to implementation of semantic web and linked data technologies in AEC (Curry et al. 2013; Pauwels and Terkaj, 2016; Pauwels et al. 2017; Rasmussen et al. 2017; Rasmussen et al. 2019; McGlinn et al. 2019). Finally, recent research also highlights a paradigm shift in the knowledge discovery and data mining community, which entails moving from mining raw data to mining the formalized knowledge directly (semantic data mining) (Lausch et al. 2015). In other words, the combination of symbolic and statistical approaches can enrich data mining processes with domain knowledge (Ristoski and Paulheim 2016) and facilitate knowledge discovery, representation and reuse, which cannot be achieved with any of these approaches alone.

Therefore, the main objective of the current research effort is to enable semantic enrichment of building performance insights discovered in operational building data in a machine-readable and reusable way. We look into how semantic annotations can be retrieved from domain experts and how they can be classified and encoded together with the building data and performance insights discovered with traditional data mining approaches to form a knowledge base. This is demonstrated for a use case in Denmark, for which frequent performance patterns and association rules have been discovered in indoor environmental quality sensor data streams. We compare the results with an alternative approach employing semantic sensor stream processing and frequent graph pattern recognition and we discuss the implications. Finally, indicate how the created knowledge base can serve as an input to providing recommendations for evidence-based decision-making in performance-oriented design.

The paper starts by outlining the background and motivation of the research (Section 1). Section 2 then outlines the methodological approaches adopted in the study. We then proceed by presenting the results from the knowledge discovery and semantic data modelling efforts that provide the input for the creation of the initial knowledge base for decision support in performance-oriented building design (Section 3). Section 4 details the linked data-based crowdsourcing effort aiming to capture the domain expert interpretations of the discovered building performance insights, as well as their semantic annotations and classifications. Section 5 presents initial semantic sensor stream processing and frequent graph pattern analysis results, thereby showcasing an alternative approach pertaining to the semantic data mining domain. Finally, Section 6 presents concluding remarks.

## 2 METHODOLOGY

Machine learning approaches for knowledge discovery allow retrieving frequent and infrequent patterns (motifs and discords respectively), anomalies and association rules in operational building data. Included in this context is also the direct mining of formalized knowledge through the use of novel semantic data mining methods. In this article, we rely on results from a previously proposed method for combination of knowledge discovery (motif discovery and Association Rule Mining (ARM)) (Agrawal et al. 1993) in operational building data and semantic data modelling for knowledge representation of a performance enriched semantic building graph (Petrova et al. 2018; Petrova et al. 2019). Association rules indicate to what extent certain events (patterns) are related to, or are potentially caused by other events (patterns). Such associations can provide valuable insights into the buildings' behaviour. Capturing this information semantically together with other meaningful building data allows applying information retrieval techniques and ultimately- implementation of the discovered knowledge in a decision support system (Petrova et al 2019).

To prepare for motif discovery and ARM, we first apply Symbolic Aggregate Approximation (SAX) (Lin et al. 2007) on the raw sensor data, which aims for dimensionality reduction and indexing with a lower bounding distance measure, i.e. the method allows reducing a large dataset to a smaller one, without losing the characteristics of the data. Motif discovery is then performed through identification of the Longest Repeated Substrings (LRS) within the SAX symbol sequences with a custom implementation of the Suffix Tree algorithm (Ukkonen 1995). Association rules between the identified frequent patterns are discovered through an implementation of the FP-growth algorithm, as both implementations are done by the help of the SPMF open-source data mining library. The output includes both the association rules, as well as their corresponding measures of interestingness, support and confidence, which show how frequently a rule appears throughout the dataset and how often it is found to be true (Agrawal et al. 1993). The association rules have thereafter been visualised for a better understanding of the correlational dependencies between the motifs and the sensor observations in which they have been discovered. Those visualisations serve as the main input to the semantic enrichment of the association rules, which is the main objective of this study.

As previously stated, to be useful, the discovered knowledge needs to be reusable, retrievable, machine-readable and integrated with other building data. Therefore, linked data techniques are used to represent the different datasets and discovered knowledge together. Home2020 was therefore modelled using the Linked Building Data (LBD) modelling principles and ontologies. More specifically, the building has been represented as a Resource Description Framework (RDF) graph by the use of the Building Topology Ontology (BOT) (Rasmussen et al. 2017). Furthermore, geographical location of the building is modelled through the use of geospatial ontologies, OpenStreetmap location and OpenWeatherMap, while sensor nodes and observations are added to the graph with the SOSA, SSN and OM (Units of Measure) ontologies. Data pertaining to heat consumption, domestic hot water use, use of appliances, HVAC system data, and HVAC design strategy for the building in accordance with the design brief requirements have also been added to provide the necessary context for the interpretation of the discovered performance patterns and rules. Occupant data has been modelled with the FOAF ontology. Finally, the discovered motifs and association rules are added to the semantic building graph by a custom "pattern" ontology (:ptn) specifically built for the purpose.

To be able to be interpreted and disambiguated, the discovered performance patterns have to be presented to domain experts in a way that allows contextualised knowledge to be continuously stored, retrieved, updated and reused. Therefore, we introduce a linked data-based crowdsourcing mechanism, which allows indoor environmental quality experts to contextualise the available building performance patterns and association rules by the use of semantic annotation tags and semantic classification.

Finally, as the above-described approach relies on traditional data mining techniques for performance pattern discovery and semantic modelling for representation of the results together with the available building data, we compare it to a direct semantic data mining approach using a frequent RDF graph pattern analysis method (Belghaouti et al. 2016).

## 3 Building Performance and Explicit Knowledge Bases

The way semantic graphs represent relations between buildings, locations, spaces, and other heterogeneous data enables the scaling and articulation of the discovered knowledge of how the existing building stock performs in a machine-readable form. Therefore, semantic graphs and ontologically demarcated data provide an infrastructure that allows knowledge disambiguation, contextualization and reuse through the rich, machine-readable semantic links between concepts. To enable building performance knowledge contextualization and demonstrate the value of semantics, the available building data needs to be treated in a way that allows capturing the evolution of the discovered knowledge over time. That includes the relation of the building performance insights to other relevant data in the AEC domain.

### 3.1 Knowledge Discovery and Semantic Data Modelling of Operational Building Data and Performance Insights for a Nearly Zero Energy Building

For this study, motifs and association rules have been discovered in indoor environmental quality sensor observations from a single family house located near the city of Aarhus, Denmark (Home2020), which was completed in 2017 and rated as nearly zero energy building (NZEB) according to the Danish energy labelling standard. The collected data is from the period 01.12.2017 to 31.10.2018 and includes measurements of energy consumption for heating [MWh], ventilation system [kWh], control system [kWh], and kitchen appliances [kWh], as well as outdoor air temperature [◦C], return air temperature [◦C], return air relative humidity [%], hot water temperature [◦C], supply air temperature [◦C], ventilation speed [steps]. Both hot and cold water consumption [m3] are also monitored. This study focuses on the indoor environmental quality data, which includes temperature [◦C], CO2 [ppm], and relative humidity [%] observations for a bedroom, a living room and a kitchen. The measurement interval is five minutes.

As described in Section 2, the sensor observations are transformed into symbolic representations with SAX. That means that the sequence of all data points are replaced by a symbolic representation such as 3222222322223333..., with each SAX symbol representing an interval of data values (e.g. 2 = [22.86950723073572, 23.704365409749624] for the Temperature observations). As a result of the SAX transformation, the output dataset consists of sequences of symbolic representations per observed variable (Temperature, CO2, Relative Humidity) for each room per month. To enable motif discovery with the LRS algorithm, co-occurrence matrices are computed on the basis of the SAX representations to identify co-occurring SAX symbols on a monthly basis. The LRS algorithm then identifies the frequent repetitive patterns in the SAX symbol sequences (Fig. 1).

```
345555 - 3 - 13;103;130;
444333 - 5 - 78;167;196;504;559;
4445555 - 4 - 29;178;244;642;
44544 - 3 - 124;222;241;
455555556 - 3 - 14;246;598;
455556 - 4 - 31;131;180;644;
54433 - 4 - 62;224;363;432;
55544 - 6 - 107;160;191;217;361;636;
555666 - 10 - 133;147;182;251;309;382;603;621;646;690;
6555554 - 3 - 157;188;723;
66655 - 8 - 141;155;186;301;428;629;681;706;
6667666 - 3 - 137;297;386;
```

Figure 1: A set of LRS found in the SAX sequences of sensor observations (Petrova 2019)

Each motif is given an unique ID, which becomes the input for discovery of the association rules. Several hundreds of motifs and rules were discovered for each observed variable, room and month. Figure 2 presents a small excerpt of rules, as well as their constituting motifs and measures of interestingness. Essential here is the fact that not all performance patterns and rules will be interesting and present unknown novel and useful insights. Further contextualisation and interpretation are required to discover the rules with the highest level of novelty and value.

```
452 ==> 489 #SUP: 1 #CONF: 1.0
453 ==> 485 #SUP: 3 #CONF: 0.6
454 ==> 481 #SUP: 1 #CONF: 0.5
456 ==> 484 #SUP: 2 #CONF: 0.6666666666666666
457 ==> 488 #SUP: 1 #CONF: 1.0
459 ==> 481 #SUP: 1 #CONF: 0.5
459 ==> 488 #SUP: 1 #CONF: 0.5
482 ==> 460 #SUP: 1 #CONF: 0.5
460 ==> 482 #SUP: 1 #CONF: 0.5
460 ==> 485 #SUP: 1 #CONF: 0.5
457 488 ==> 378 #SUP: 1 #CONF: 1.0
378 488 ==> 457 #SUP: 1 #CONF: 0.5
```

Figure 2: An excerpt of the set of association rules obtained for the living room in Home2020 (Petrova 2019)

That may include considerations related to the combined effect of the support and confidence. Either way, it requires a domain expert to identify the strong and interesting rules that indicate novel building performance insights, thereby enriching them with semantics and transforming them from statistical output to actionable knowledge. The semantic enrichment of association rules requires a semantic data infrastructure that would allow the storage, retrieval, interpretation and reuse of the contextualised knowledge.

To allow the latter, all motifs and association rules have been modelled together with the available building data by the use of the PATTERN ontology, indicating their ptn:confidence, ptn:absoluteSupport, and ptn:relativeSupport measures. The modelled association rules (e.g. inst:associationRule_1) are linked to the sensor nodes they are related to with ptn:hasAssociationRule predicates. The constituting motifs for the association rules are represented as ordered lists of motifs for the left-hand side (ptn:LHS) and right-hand side (ptn:RHS) of each rule (Fig.3).

Figure 4 represents the resulting semantic building graph, which includes the available building data, system and occupant data, actuator and sensor data including data points for all observed variables, contextual data (geolocation and weather data), as well as the motifs and association rules discovered in the sensor data.

```
inst:associationRule_1
  rdf:type ptn:AssocationRule ;
  ptn:LHS (inst:Motif_45) ;
  ptn:RHS (inst:Motif_137) ;
  ptn:confidence "0.5"^^xsd:double ;
  ptn:absoluteSupport "1"^^xsd:double ;
  ptn:relativeSupport "0.5"^^xsd:double .

inst:motif_45
  rdf:type ptn:Motif ;
  ptn:SAXsequence "11122"^^xsd:string ;
  ptn:space inst:Kitchen ;
  ptn:month "8"^^xsd:string ;
  ptn:SAXsequenceFull (inst:SAXSymbol_91983cb8-4dd3-4544-a1fe-7
    b177e237bc0 inst:SAXSymbol_91983cb8-4dd3-4544-a1fe-7b177e237bc0
     inst:SAXSymbol_91983cb8-4dd3-4544-a1fe-7b177e237bc0 inst:
    SAXSymbol_41fadfdb-6560-4e96-9a7f-bc405f453452 inst:
    SAXSymbol_41fadfdb-6560-4e96-9a7f-bc405f453452 );
  ptn:observedVariable "CO2"^^xsd:string .

inst:SAXSymbol_36ef82d8-57c9-4e0a-a0bc-c1c66404b02b
  rdf:type ptn:SAXSymbol ;
  ptn:symbol "5"^^xsd:int ;
  ptn:lowerBound "645.651281059915"^^xsd:double ;
  ptn:upperBound "700.959674546294"^^xsd:double .
```

Figure 3: A snippet of the RDF graph with motifs and associated rules (Petrova 2019)

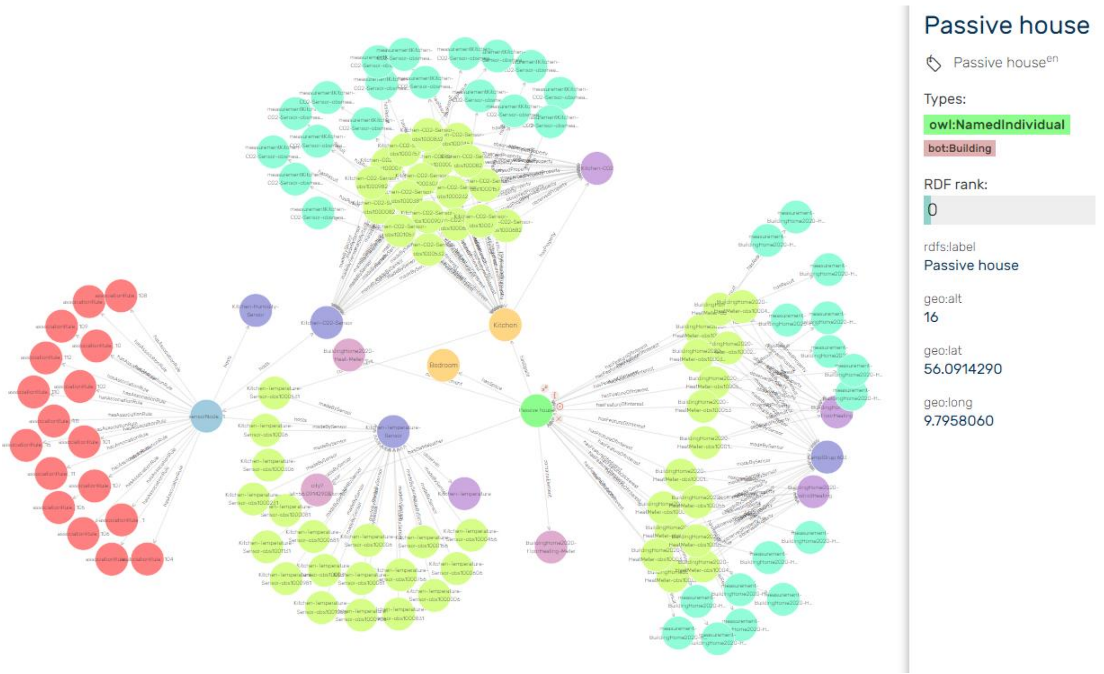


Figure 4: Semantic graph of Home2020 containing the building URIs and the related spaces, sensor nodes, occupants, sensor data and the motifs and association rules discovered in the data (Petrova 2019)

## 3.2 Visualization of Building Performance Patterns and Association Rules

The performance-enriched and contextualized semantic building graph allows dedicated information retrieval, and most importantly provides both the necessary infrastructure for capturing domain expertise and the input for interpretation and semantic enrichment of the association rules. To allow that, the knowledge embedded in the graph needs to be presented to the domain experts in a structured way, which requires a user interface and a data model that allows to store the meaning, be able to update it and embed it in the knowledge base for further reuse in evidence-based design processes. Therefore, to facilitate the process of knowledge interpretation, the association rules and corresponding patterns have been visualized to enable a better understanding. Figure 5 shows the visualization of association rule 453 ==> 485 #SUP: 3 #CONF: 0.6, which means that every three out of five times when pattern 453 appears throughout the dataset, pattern 485 also appears. The figure exemplifies the motifs with their ID and SAX sequences, the interval that the symbols are in, the observed variables in which they appear, the relationship between them and highlights the support measure. Such a visualization enables a much easier expert interpretation than the formal output of the algorithm as visualized in Fig. 2.

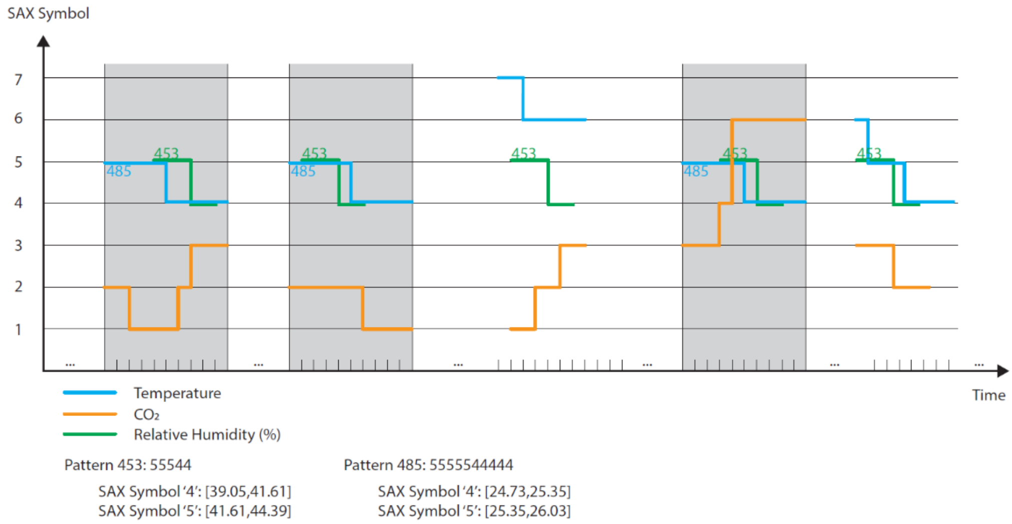


Figure 5: A visualization of an association rule discovered in indoor environmental quality data, the motifs that it contains of and their corresponding SAX sequences (Petrova 2019)

That way and for the given example, it is much easier to confirm that whenever the indicated interval sequence in Relative Humidity occurs, there is a 60% likelihood that the corresponding interval sequence in Temperature also occurs throughout the entire dataset. Being visualised, the association rules and motifs can then be semantically enriched through an appropriate data model that fits the structure of the knowledge base.

## 4 Capturing Domain Expertise - The Effect of the Crowd on the Semantic Enrichment of Association Rules

To achieve the semantic enrichment of association rules, this study aims to combine the powerful pattern recognition capability of machines with the domain expertise of humans. It is hereby important to distinguish between domain expertise or knowledge with regards to formal ontologies for semantic representation of data, and domain knowledge in terms of the human expertise required to interpret building performance patterns.

In this study, both concepts are applied accordingly, as ontologies are used for knowledge representation and storing in the semantic graphs and human expertise is harvested for the semantic enrichment of the association rules. The provided human domain expertise is also mapped to a formal ontology and added to the semantic graph. Figure 6 presents the architecture of the intended knowledge capture system and the interaction between the experts and the knowledge base during the interpretation and semantic enrichment of the association rules.

Fundamentally, the defined semantic enrichment approach and the corresponding system architecture rely on the concept of the "crown truth" and the notion that collecting annotations of the same objects of interpretation across a crowd reduces subjectivity, provides more meaningful representations and much more reasonable interpretations. In other words, the semantic enrichment system relies on the dominance of the human domain expertise, which is solicited from an expert crowd. The expert crowd in this case consists of indoor environmental quality experts with various levels of expertise, years of experience, area of expertise (thermal, visual, acoustic, atmospheric), etc. All association rules are stored in the knowledge base and can be retrieved as soon as a domain expert logs in and activates their profile. For each association rule, each expert can define new meaning by annotation, perform classification with semantic tags or review existing interpretations by upvoting or updating. That input gets stored in the semantic graph together with a reference to the Uniform Resource Identifier (URI) of the corresponding domain expert who provided the input. Under the effect of the crowd, the association rules with highest level of interestingness and usefulness become visible, including annotations that would allow retrieval of the semantically rich building performance metrics. The following section will, therefore, define the technical aspects of the outlined expert crowd-centric semantic enrichment mechanism.

## 4.1 Crowdsourcing Building Performance Patterns

Crowdsourcing as an approach responds to the above-described notion of the crowd truth and provides an opportunity to capture collective intelligence and knowledge that are otherwise dispersed (Schenk and Guittard 2011). As a result, crowdsourcing has received major attention in various domains, e.g. image recognition, fabrication, design (Xiang et al. 2018). That also applies to the Semantic Web domain, where crowdsourcing techniques have been used for semantic annotation, ontology engineering, knowledge base curation and linked data quality assurance (Sack 2014; Sarasua et al. 2015). AEC research demonstrates the implementation of crowdsourcing for BIM-based construction material libraries through annotation of site photo logs (Han and Golparvar-Fard 2017), annotation of construction workers on site (Liu and Golparvar-Fard 2015), co-creation of infrastructure as-built BIM models and infrastructure maintenance (Consoli and Reforgiato 2015).

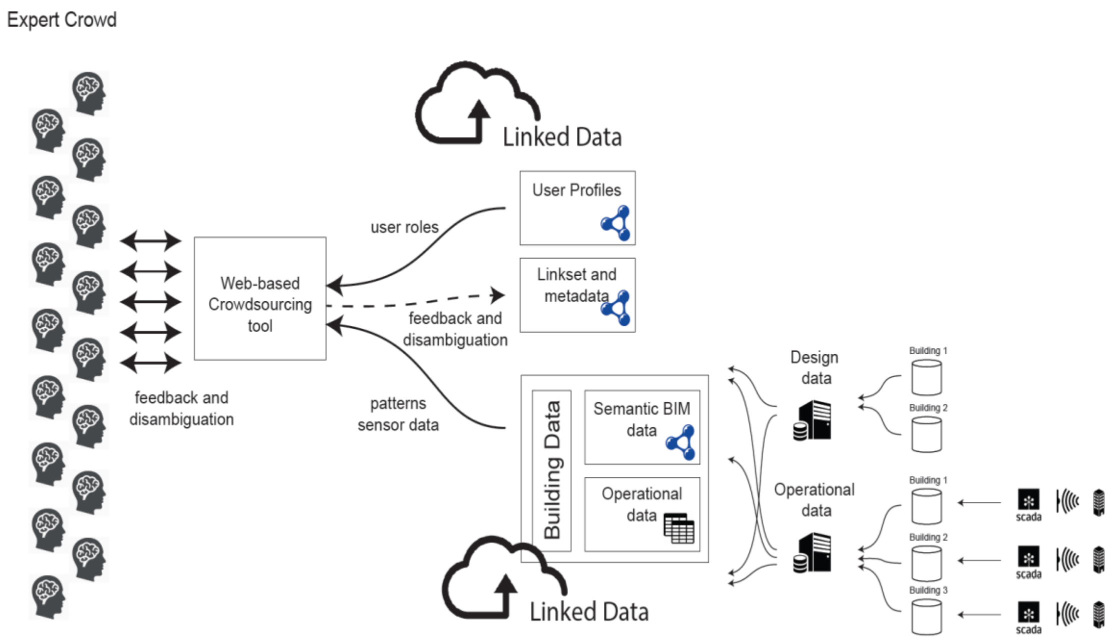


Figure 6: System architecture of the proposed crowdsourcing system (Petrova 2019)

The adopted type of crowdsourcing platform in this research effort is what is defined as “Information Pooling”, i.e., based on additive aggregation of distributed information and aiming to integrate diverse opinions, assessments, predictions or other kinds of information from contributors (Blohm et al. 2018). Using that principle, the expert annotations are collected through the crowdsourcing platform and stored directly in the semantic graph. Domain experts are hereby modelled using the FOAF ontology, whereas their input is modelled according to the schema.org ontologies, which provide an opportunity to use Review and Commenting mechanisms. In this case, expert Reviews and Comments are linked directly to the schema:CreativeWork class. In addition, the schema:Person class can also be used for defining the human experts.

Alternatively, the Review ontology can also be used, however, schema.org provides more flexibility and dimension to the linked data-based crowdsourcing effort, as it allows storing votes (e.g. schema:upvoteCount). Furthermore, Reviews, Comments, and CreativeWorks can be combined and further enriched by adding metadata to each of them (agent, about, dateCreated, text, etc.). That allows a much bigger flexibility in terms of semantic annotation, tagging and adding of descriptions for further clarification of the expert interpretations. This principle and resulting data model is depicted in Fig. 7.

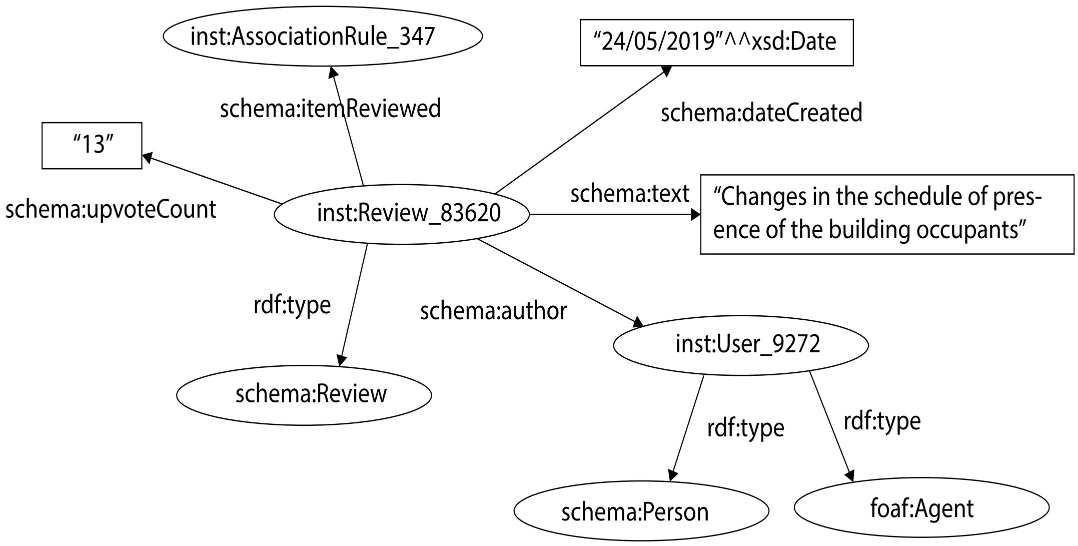


Figure 7: Data model for semantic annotation and interpretation of association rules (Petrova 2019)

## 4.2 Semantic Annotation and Classification of Association Rules

So far, the described approach allows the domain expertise to be input and stored in the semantic graph in the form of reviews and descriptions defined by the human experts. However, it does not provide semantically definitive tags or classifications, which are necessary for information retrieval. Thus, semantic tags have been further created so that the provided reviews and descriptions could be formally annotated and classified. The tags have been created on the basis of the most usual causes of any frequent performance patterns appearing in sensor observations from buildings. Typically, such patterns are related to dynamic parameters that influence building performance directly. The semantic tags for annotation of association rules are, therefore, identified by the most probable reason for the occurrence of the patterns and defined as (1) external conditions, (2) occupant behaviour, (3) system performance, (4) design and (5) construction. Thus, expert input is classified and annotated with these tags.

Furthermore, the crowdsourcing system allows adding previously undefined subtags, should such be deemed necessary by the domain experts for clarification of a rule. Figure 8 illustrates the principle behind the semantic tagging and classification. Naturally, the data model has to be implemented in an application, which the expert crowd can interact with to complete the semantic enrichment of the association rules. However, the development of such an application and user interface is beyond the scope of this paper. Finally, even with the semantic annotation and classification in place, it is still not possible to assess the value of the semantically enriched association rules. In other words, further input is required to filter interesting association rules that point to abnormal or unexpected patterns and exclude the expected dependencies. To achieve that, we rely on the previously mentioned Upvote option as provided by the schema.org ontology (schema:upvoteCount), thereby allowing the domain experts to perform Input (Annotation)- Review- Upvote cycles and enrich association rules, but also indicate a level of interestingness that is based on both statistical measures and expertise. Figure 9 depicts the proposed crowdsourcing mechanism.

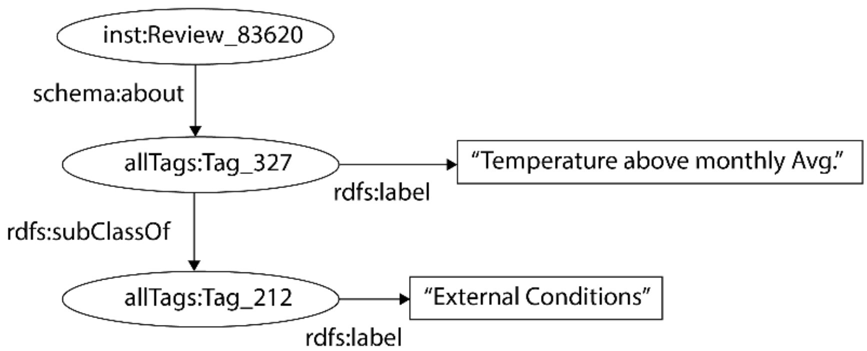


Figure 8: Semantic tags for classification of expert reviews (Petrova 2019)

## 5 Direct Semantic Stream RDF Graph Pattern Discovery

As seen so far, ARM is an effective method of discovering frequent patterns in building performance. The described crowdsourcing approach can also be effective in the semantic enrichment and interpretation of the discovered rules. However, it has to be acknowledged that the sole reliance on the users' intervention can be time-consuming and error-prone, especially in the cases of large amounts of data. Also, the measures of interestingness (confidence and support) consider the knowledge at instance-level and any available knowledge at schema level is disregarded, which may have a negative impact on the actual interpretation. In this regard, several studies suggest RDF stream processing as an alternative, i.e. converting the raw sensor data streams into RDF streams and use semantic data mining approaches on the resulting graph to identify association rules. Therefore, we further look into the RDF stream processing and graph pattern recognition method and discuss to what extent it could be compared to the previously described approach.

## 5.1 RDF Stream Processing and RDF Graph Pattern Recognition

Several researchers state that to enable stream processing, we should move from storing semantic data in batches and querying it ("one-time semantics") to using query languages with streaming extensions to perform continuous queries on the semantic data streams ("continuous semantics") (Della Valle et al. 2009; Calbimonte et al. 2012). In that relation, the main steps to publishing sensor data as RDF streams have also been defined and include conversion from sensor data streams to RDF streams, storing the resulting RDF streams, and linking them with other relevant datasets. That requires the selection of relevant ontologies, defining an appropriate mapping language for conversion, selection of continuous query languages and choosing relevant datasets to link to (Llanes et al. 2016) (Fig.10).

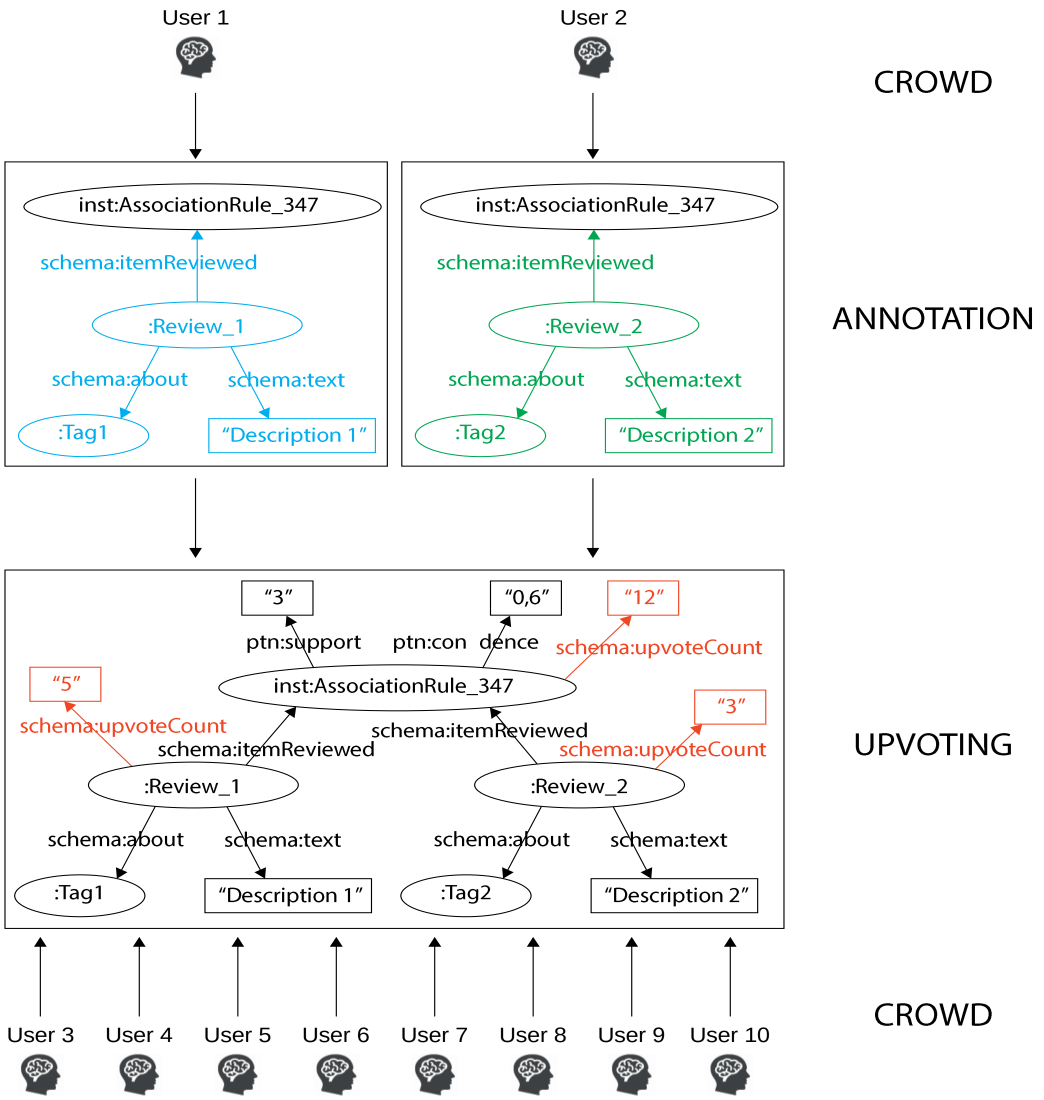


Figure 9: A snippet from the semantic graph containing the expert annotations and reviews of discovered association rules and the crowdsourcing process (Petrova 2019)

To demonstrate the principle of pattern recognition within the RDF graph structure, we employ a method for frequent RDF graph pattern detection in semantic data streams, which relies on the graph predicates (Belghaouti et al. 2016).

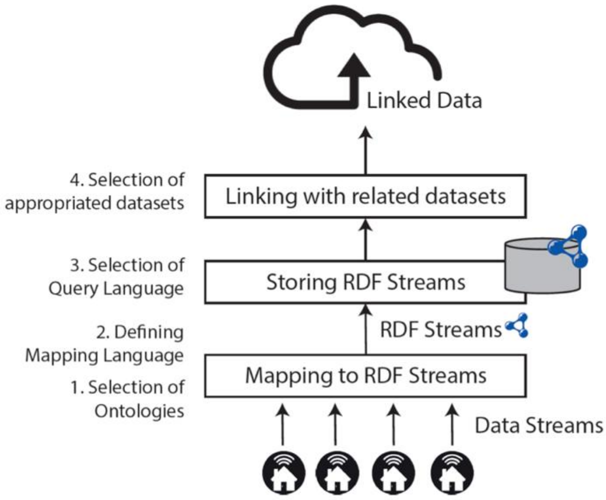


Figure 10: Process of publishing sensor data streams as RDF streams

Each graph in the stream data can be represented as a directed star graph as shown on the left side in Fig. 11. The proposed method relies on the fact that the streams are represented according to particular ontologies, which means that most streams will be relatively uniform and expose a very frequent RDF graph structure.

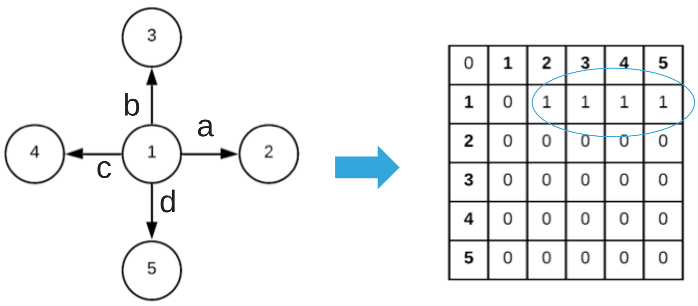


Figure 11: A directed star graph as represented in a RDF stream and the corresponding adjacency matrix based on the graph predicates, based on Belghaouti et al. (2016)

According to Belghaouti et al. (2016), RDF graphs could then be represented using adjacency matrices, however, such an approach would not be fully efficient and is not suitable for RDF graphs as it will result in a very sparse matrix (right in Fig.11). Therefore, it is proposed to reduce the associated adjacency matrix to a bit vector (Fig.12).

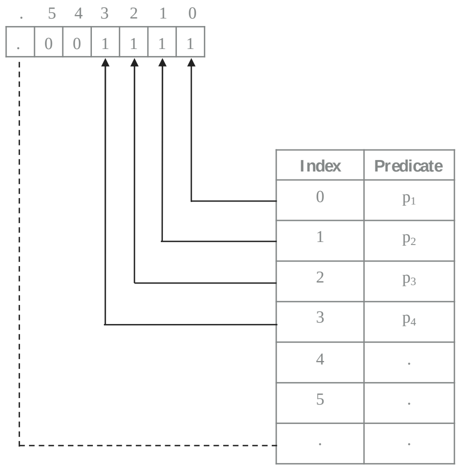


Figure 12: Principle of construction of the graph pattern using a bit vector based on the graph predicates, based on Belghaouti et al. (2016)

Based on the bit vector it is then possible to construct the Predicates Hash Table (PHT), which contains all the detected predicates in RDF graphs of an input stream and holds them, as well as the Graph Hash Table (GHT), which detects all the RDF graph patterns and holds them. In theory, that makes it possible to observe the evolution of the stream and the detected frequent RDF graph patterns. However, since the predicates are identical, the only change will be in the numerical value of the observations, which the graph pattern recognition method cannot account for. To demonstrate the detection of the graph patterns, we consider again the building graph of Home2020 illustrated in Figure 4 and extracted star shaped graphs storing the Relative Humidity and Temperature observations from the indoor environmental quality data stream from the kitchen. As seen from the examples, the RDF graph structure is rather consistent, also in terms of ontological representation, which is consistent with the outlined in (Belghaouti et al. 2016). The observed differences stem from the type of the observed variables and their corresponding units of measure.

```
inst:Kitchen-Humidity-Sensor-obs1132308
        rdf:type sosa:Observation ;
        sosa:hasFeatureOfInterest inst:Kitchen ;
        sosa:hasResult inst:measurementKitchen-Humidity-Sensor-obsmeas1132308 ;
        sosa:madeBySensor inst:Kitchen-Humidity-Sensor ;
        sosa:observedProperty inst:Kitchen-Humidity ;
        sosa:resultTime "22/01-2018 10:35:45"^^xsd:dateTime .

inst:measurementKitchen-Humidity-Sensor-obsmeas1132308
        rdf:type om:Measure ;
        om:hasNumericalValue "43.0"^^xsd:double ;
        om:hasUnit om:percent .


inst:Kitchen-Temperature-Sensor-obs2913631
        rdf:type sosa:Observation ;
        sosa:hasFeatureOfInterest inst:Kitchen ;
        sosa:hasResult inst:measurementKitchen-Temperature-Sensor-obsmeas2913631 ;
```

```
                    sosa:madeBySensor inst:Kitchen-Temperature-Sensor ;
                    sosa:observedProperty inst:Kitchen-Temperature ;
                    sosa:resultTime "14/04-2018 22:15:45"^^xsd:dateTime .

inst:measurementKitchen-Temperature-Sensor-obsmeas2913631
                    rdf:type om:Measure ;
                    om:hasNumericalValue "24.0"^^xsd:double ;
                    om:hasUnit om:degreeCelsius .
```

Following the described methodology, we can then construct the bit vector of the graph and identify the repetitive graph pattern. That is hereby demonstrated with the Temperature observation (Fig.13). As seen in the single example below, the detected frequent RDF pattern is rather different in nature from the performance patterns identified and interpreted earlier. While the graph pattern presents a variety of semantically rich and highly contextual data, it does not contain any explicit semantics related to building performance behaviour. As it is identified based on the graph predicates, the presented graph pattern could provide information about the evolution of the stream over time if predicates change, but any behavioural insights, correlations between performance variables or causations need to be discovered in alternative ways.

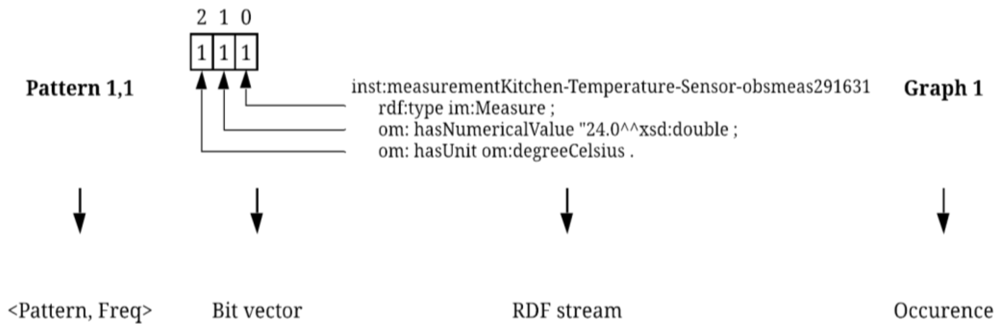


Figure 13: RDF graph pattern detection in indoor environmental quality data

## 6 Conclusion

The rapidly increasing amount of monitored building data allows using novel statistical and symbolic AI approaches for discovery of valuable knowledge in building performance. Such methods have come a long way in processing vast amounts of data, finding patterns and relationships and predicting trends, thereby enhancing human decision-making in the building performance improvement domain. However, regardless of how powerful pattern recognition, knowledge representation or information retrieval techniques are applied, the interpretation of the discovered building performance patterns is in the hands of the domain experts, who usually need to apply domain expertise to interpret their meaning and implications on the overall building performance. Data analytical output usually does not convey any explicit semantics and its value is dependent on the contextualization and interpretation stemming from domain expertise.

This paper approaches this issue with a novel methodology for semantic enrichment of discovered frequent repetitive patterns and association rules in monitored indoor environmental quality data from a passive house in Denmark. By applying motif discovery and Association Rule Mining, we obtain patterns and rules that are represented and stored in a semantic building graph together with other available building data by the use of several domain ontologies. For semantic enrichment, interpretation and contextualization, we devise a linked-data based crowdsourcing mechanism, which captures domain expertise in the form of semantic annotation and classification. That results in a comprehensive knowledge base that stores not only building data and indoor environmental quality sensor observations, but also building performance patterns and their meaning. Such a knowledge base can be of high value in evidence-based design processes and building performance assessment and improvement. Furthermore, we compare the applied approach, which combines knowledge discovery and semantic data modelling to a direct RDF graph pattern mining approach to assess feasibility and potential.

With regards to the latter, several important observations need to be addressed. First and foremost, while machine learning approaches for Association Rule Mining are rather effective for detecting frequent patterns, there are several manual steps related to data treatment and parameter selection. Moreover, a traditional data mining approach such as this one analyses the data in batches and the discovered knowledge is, therefore, only locally valid for the dataset in question. Second, while Semantic Web and linked data technologies allow representing and storing the discovered knowledge, but the value of the discovered performance patterns and rules lies in their meaning, which is not explicit, unless interpreted by a domain expert. And while the presented crowdsourcing mechanism provides a solution to that, it still has to be acknowledged that the contributions of the expert crowd used for interpretation and semantic enrichment of the rules may vary. That means that an additional validation layer may be necessary. It has to be noted, that even though the semantically enriched performance patterns are stored in the graph and can be retrieved, they do not provide direct solutions in terms of, for instance, design decision support or building performance optimization. They serve merely as an evidential layer to human decision-making.

Finally, being based on the graph predicates, the demonstrated frequent RDF graph pattern detection method could provide an insight about the evolution of semantic sensor data streams based on the graph predicates, but does not provide any actual building performance insight, as the pattern recognition is solely based on the graph structure and not on the numerical values of the sensor observations. Therefore, future research in that direction may rely on graph alignment techniques to harvest the benefits of both methodologies.

The proposed crowdsourcing mechanism can be of high value to engineering practice in several ways. By combining both knowledge discovery and semantic data modelling approaches, the crowdsourcing platform establishes the missing link between machine learning output and the human domain knowledge necessary for its interpretation. That enables the reuse of highly valuable and complex engineering knowledge and can also serve as an educational mechanism for understanding dynamics in building performance and indoor environmental quality parameters. The system also enables the creation of a feedback loop between building operation and design and helps practitioners learn from the behaviour of the existing building stock, engage with the streaming sensor data, understand it and bring out the value in it.

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# DIGITAL TWINNING OF CONSTRUCTION OBJECTS: LESSONS LEARNED FROM POSE ESTIMATION METHODS

**Fan Xue[1], Hongling Guo[2] and Weisheng Lu[3]**

**Abstract:** Productivity and safety in the construction industry have long been hindered by the many uncertainties and lack of awareness in the semi-controlled site environment. The digital twinning of construction objects aims at offering digital replicas with real-time, trustable evidence for automated monitoring, human-centric decision-making, or fully automatic cyber-physical systems. This paper revisits the pose estimation methods for the digital twinning of various on-site construction objects, including construction components, equipment, and humans. From a machine learning perspective, all the pose estimation methods can be categorized into four classes, i.e., filtering, supervised, reinforcement, and unsupervised. The inputs, processes, output, and target objects of each class are introduced with demonstrative cases. Comparisons on the pros and the cons of the methods reveal the best choices for digital twinning under different objectives, such as a safer site and more productive construction, as well as constraints such as pose accuracy, computational time, and overall cost. The complexities of digital twinning different construction objects are compared to explain the distribution of existing cases in the literature. Opportunities and possible research directions in the new era of AI and blockchain are recommended at the end.

**Keywords:** Digital twin, Pose estimation, Machine learning, Digital construction site, Smart construction object.

## 1 INTRODUCTION

The construction industry has been encountering difficulties in its practices, such as endangered productivity and safety in semi-controlled site environments. Compared to other industries with controlled environments, such as manufacturing, the construction industry has seemed “backward” in the past decades (Woudhuysen and Abley 2003). Information and communication technology (ICT), such as the Internet of things (IoT), laser scanning, sensor network, and geographic information system (GIS), has been successfully applied to the monitoring and automation of construction objects, including construction components, equipment, and humans (Ahuja et al. 2009).

A digital twin is “a virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning, and reasoning,” according to the UK National Infrastructure Commission (2017). Digital twinning of construction objects, as shown in Figure 1, offers digital replicas with real-time information, which can improve the traceability and controllability of the construction objects. Digital twinning of construction objects will be promising and impactful,

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according to its records for other sophisticated systems, such as aircraft, wind turbines, and smart trains (Tuegel et al. 2011). In this sense, digital twinning is the equivalent to the “physical-to-cyber” subsystem of a cyber-physical system (CPS) that aims to “monitor and control the physical processes” (Lee 2008).

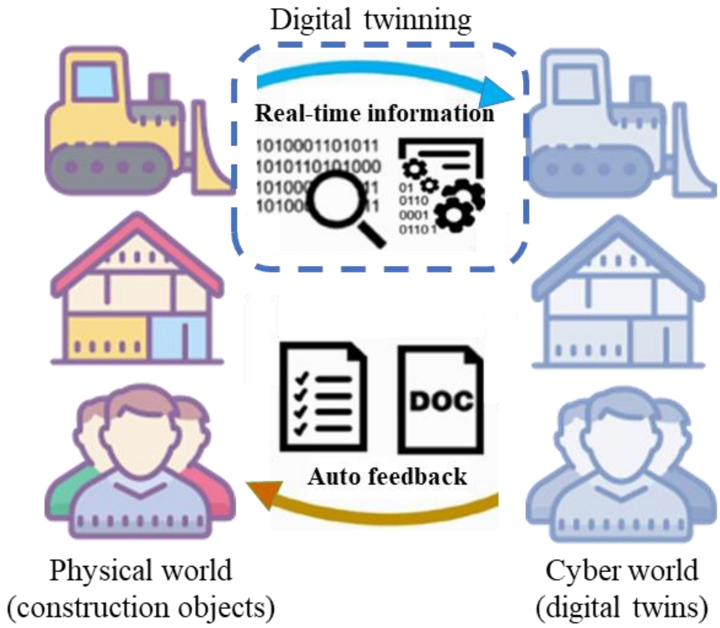


Figure 1: Digital twinning of construction objects and their positions in a cyber-physical system.

The 3D pose, as a synthesis of position, orientation, and potential purpose of a construction object, is a piece of key information for digital twinning. Pose estimation refers to the identification of such accurate position and orientation, as well as an understanding of potential purposes, from ICT sensor data for construction objects. Pose estimation methods have been investigated sporadically in construction scenarios, such as smart construction object (SCO), as-built building information model (BIM) reconstruction, construction virtual reality (VR), 4D city information model, and high-definition 3D map (Niu et al. 2016; Schwarz 2010). However, the varieties of construction objects, data inputs, and application scenarios make a one-size-fits-all method impractical. Furthermore, digital twin applications demand higher performance, for example, in near-time responsiveness and pose accuracy.

This paper aims to revisit the existing pose estimation methods in the new context of digital twinning of construction objects. In specific, a four-class taxonomy—filtering, supervised, reinforcement, and unsupervised—is borrowed from the domains of machine learning and signal processing. Section 2 briefs the research methodology. The representative methods in the four classes were demonstrated with empirical cases in Section 3. The discussion and recommendations appear in Section 4, and the conclusion is given at the end of this paper.

## 2 RESEARCH METHODS

This study employs a comparative study on the pose estimation of construction objects. First, four models are derived from the conceptual digital twinning model in Figure 1 based on the taxonomy of machine learning methods. Then, demonstrative cases are surveyed from the literature to cover the combinations of the four classes and the three types of construction objects, i.e., components, equipment, and humans. The pros and cons of the pose estimation methods are summarized, and recommendations are given based on the demands of digital twin applications.

This study proposes a four-class taxonomy for pose estimation methods in construction, as shown in Figure 2. Due to the 'mapping-A-to-B' nature of the identification of pose information from ICT data, three classes (supervised, reinforcement, and unsupervised) are borrowed from machine learning theories. Those methods without any learning characteristics are classified as 'filtering' methods. Meanwhile, each class of method requires unique domain-specific knowledge.

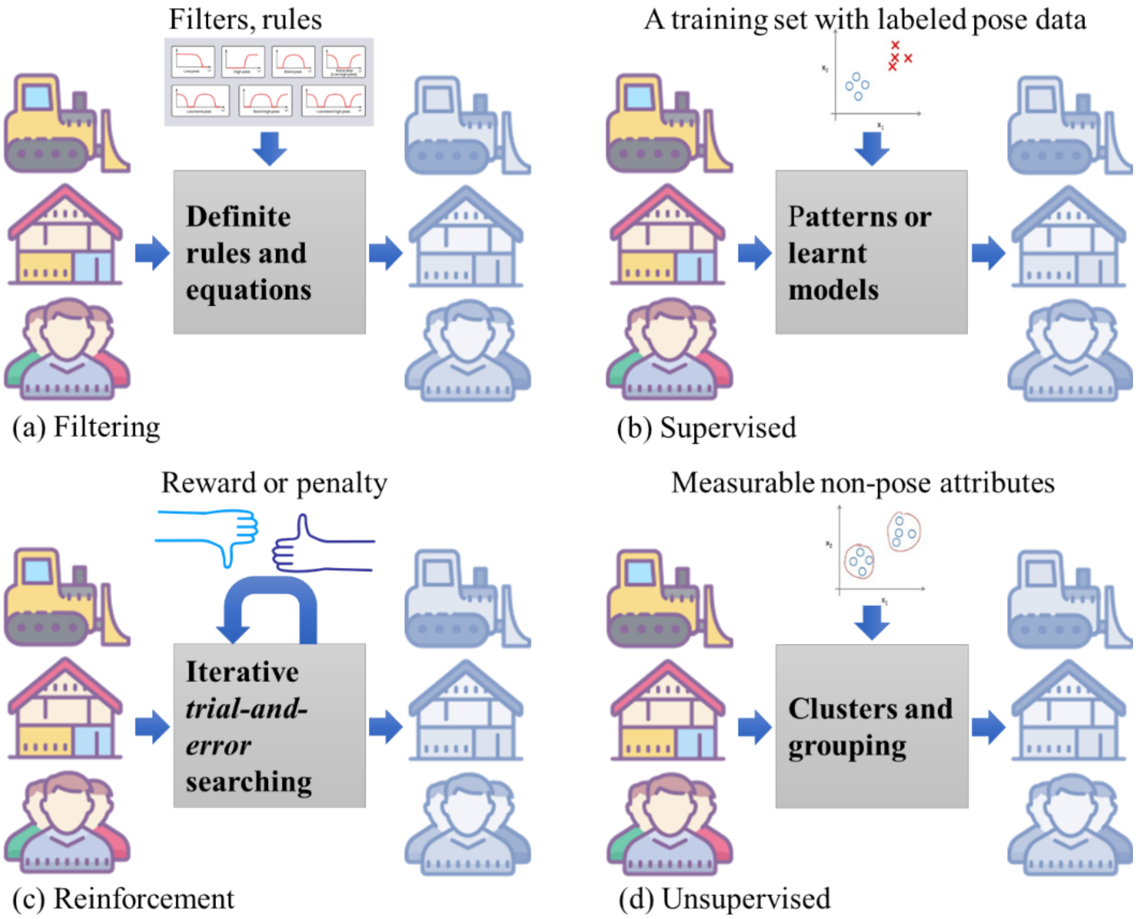


Figure 2: The four proposed classes of pose estimation methods in construction.

A literature search was conducted on Google Scholar, with the query term '(pose estimation) (construction) (human OR equipment OR facility)' and a publication date in or after 2011. The top 500 results were initially screened for the most representative cases according to the titles and abstracts within the two focused domains of construction management and computer-aided technologies (CAx). Then, the publications were furthered filtered according to the richness of information they contained on poses (e.g., position, orientation, and shreds of evidence of purposes) and ordered descending according to the average number of citations per year. A snowballing process was then executed for the top candidate papers to include the missing query keywords. The process produced nine representative cases, as listed in Table 1, of existing pose estimation in construction.

Table 1: Representative cases of pose estimation of various construction objects.

| | Components | Equipment | Human |
|---|---|---|---|
| Filtering | Niu et al. (2019) | Zhang et al. (2012) | Yan et al. (2017) |
| Supervised | Jin and Lee (2019) | Golparvar-Fard et al. (2013) | Han and Lee (2013) |
| Reinforcement | Xue et al. (2019) | – | – |
| Unsupervised | Kashani and Graettinger (2015) | Chen et al. (2017) | – |

The cases in Table 1 covered nine out of the 12 combinations of the four classes of methods and the three types of construction objects. The missing three entries were related to the reinforcement methods for estimating equipment and human poses and unsupervised methods for human poses. Three amidst the nine papers, i.e., Zhang et al. (2012), Golparvar-Fard et al. (2013), and Han and Lee (2013), were published between 2012 and 2013, which indicated that quite a portion of pose estimation studies was established in construction before the advent of the concepts of digital twin and cyber-physical systems. Besides, many supervised learning methods that apply to construction were excluded from this study if they oversimplified the target pose information such as a 'yes/no' estimation of whether a 2D image is a worker or a truck.

# 3 POSE ESTIMATION OF CONSTRUCTION OBJECTS

## 3.1 Filtering methods

A filtering method applies fixed rules and processes, often in the form of definite rules and equations, as shown in Figure 2a. The input data contains the pose data, yet with noise and uncertainty. Based on the filter patterns or rules, the processing can result in more accurate and stable pose data. Zhang et al. (2012) developed an early real-time positioning system in 2012 based on the ultra-wideband (UWB) technology. The method, as shown in Figure 3a, employed eight sensors to measure a mobile crane's pose changes in distances of a few meters. The results showed that errors up to two meters were corrected by a 3D velocity filtering method from the raw sensor data.

Yan et al. (2017) integrated two inertial measurement unit (IMU) sensors in for estimating a construction worker's poses of head, neck, and trunk, as shown in Figure 3b. They cross-referenced the sensor data via a human backbone model and filtered and warned the 'Not Recommended' poses in real-time. For example, once the angle of trunk inclination is over 60° during manual operations, there would be a high risk of lower back pains.

Niu et al. (2019) integrated more types of sensors, including IMU, altimeter, and global positioning system (GPS) on an IoT device, for monitoring precast beam hoisting. They also applied a 3D velocity filter and identified the beam's poses and motions, including swings and rotations in the air, in real-time. The estimated poses were utilized for analyzing the near-miss safety issues as well as productivity. The 4D pose traces of the hoisted beams were visualized online in near real-time on an open GIS engine called Cesium.

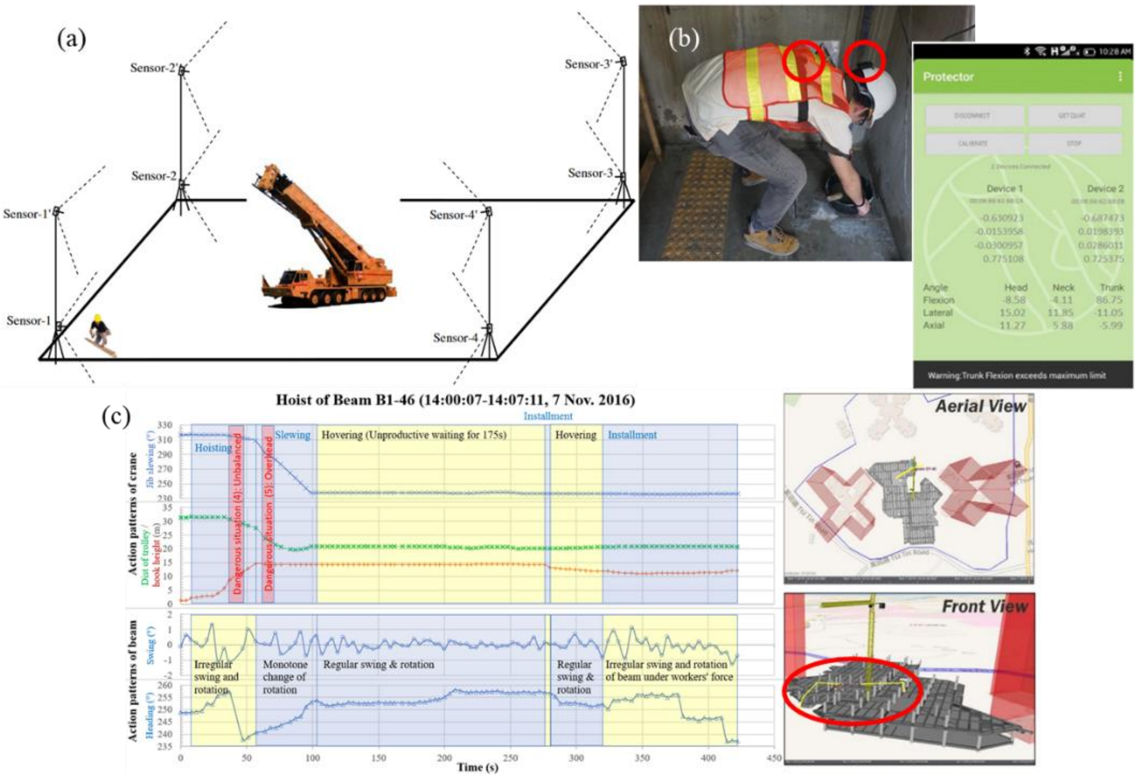


Figure 3: Filtering methods of pose estimation. (a) Sensor settings for a crane in Zhang et al. (2012); (b) Sensors (as circled) and real-time pose warnings (Yan et al. 2017); (c) Multi-sensor fusion and pose trace (as circled) in hoisting (Niu et al. 2019).

## 3.2 Supervised methods

A supervised method first summarizes the pose patterns or learns a meta-model from the given training data, then applies the learned patterns or models to the input data, as shown in Figure 2b. The input data table does not contain the pose data, but a list of relevant data columns called 'attributes.' Meanwhile, the training data is a table comprised of all the attributes and annotated label columns about the target pose. That is why the learned patterns or models are applicable to the input data for pose estimation. Golparvar-Fard et al. (2013) investigated the pixels' gradient-based movements and orientations in a crane video, and applied a multiple binary SVM classifiers to estimate the poses and activities, as shown in Figure 4a. They reported average accuracies at 86.33% and 98.33% for categorical actions of excavators and trucks, respectively.

Han and Lee (2013) was another early vision-based supervised method using dual cameras. The two cameras were set up to cover a target area from different view angles. First, the cameras estimated 2D poses independently through a pre-trained supervised learning model based on the Histogram of Oriented Gradient (HOG) descriptor. Then, the two 2D poses were matched into a 3D pose, as shown in Figure 4c. The recall of unsafe action detection was 88%, and the precision was also 88%.

Figure 4b shows the 3D reconstruction process of a pipeline system from a laser-scanned point cloud in Jin and Lee (2019). They applied the random sample consensus

(RANSAC) to estimate the cylinder axes and employed principal component analysis (PCA) eigenvalues for distinguishing linear and curved regions based on the Catmull–Rom spline. The recall rates of the pipes were around 85% to 90%, while the computational time was about 30s for 60-90 pipes (i.e., less than 0.5s per pipe on average).

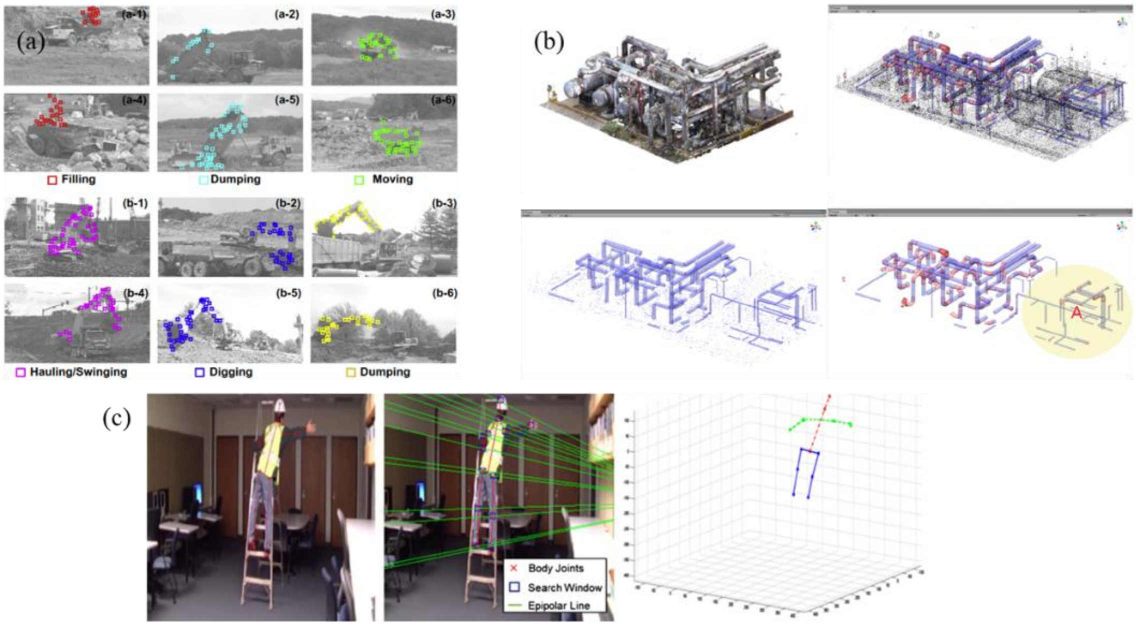


Figure 4: Supervised methods of pose estimation. (a) Learned motion features of equipment (Golparvar-Fard et al. 2013); (b) Pipelines 3D reconstruction (Jin and Lee 2019); (c) Dual-camera worker pose estimation process (Han and Lee 2013).

## 3.3 Reinforcement methods

In contrast, reinforcement methods were mentioned the least often in the literature. Reinforcement methods in machine learning aim to understand and automate goal-directed learning and decision-making by learning from interaction with an environment (Sutton 2018). In pose estimation, it involves repeated iterations of trial-and-error searching for the best pose, as shown in Figure 2c. Thus, a reward or penalty function is required, rather than the filters and annotated training pose data, is necessary for reinforcement methods. Xue et al. (2019) presented a reinforcement method named semantic registration based on an error function and explicit optimization algorithms, as shown in Figure 5. The test results on a 293 auditorium chairs case showed the recall and precision were around 85%, at 5.3s average computational time for each chair.

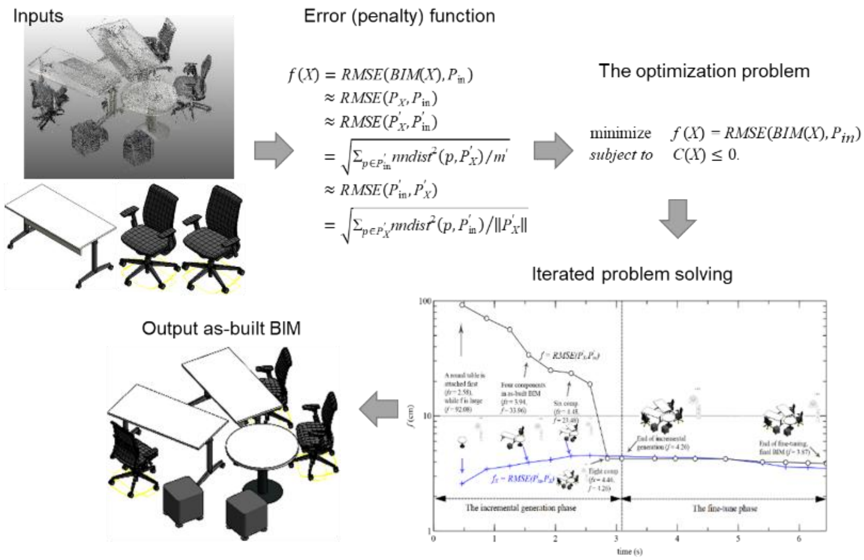


Figure 5: A reinforcement method of pose estimation in Xue et al. (2019).

### 3.4 Unsupervised methods

The unsupervised methods, or clustering, require the least domain knowledge in the four classes. Instead, once some non-pose attributes in the input data table are measurable, e.g., float or integer numbers, the input data records can be clustered to a few sets or a closeness-based hierarchy, as shown in Figure 2d. Although the output clusters are often not able to predict the poses directly, they are effective descriptors that recap and conceptualize a large volume of data. Thus, unsupervised methods are popular in the automated pre-processing of 3D point clouds (Chen et al. 2017; Jin and Lee 2019). Kashani and Graettinger (2015) present a direct use of the clusters for detecting rooftop damages from ground-based LiDAR data, as shown in Figure 6a. They tested the combinations of unsupervised methods and evaluation criteria and found that the Elbow method and the Calinski-Harabasz criterion resulted in an 82% correct estimation. The resulting clusters also reflected the poses of the roof elements.

Chen et al. (2017) developed a principal axes descriptor (PAD) of the cluster of points for the recognition of construction equipment. Figure 6b shows the unsupervised part. The input points were pre-processed for background removal using ground erosion. Then, Chen et al. applied an unsupervised Euclidean clustering method, where the nearest points were grouped, and isolated noise points were removed. The experimental results showed the new PAD was robust against various equipment poses. Next, after a round of supervised recognition, the precision and recall of recognizing excavators achieved over 90%, but the recall for backhoe and front loaders was no more than 75%, while the precision for bulldozers and dump trucks was no more than 60%.

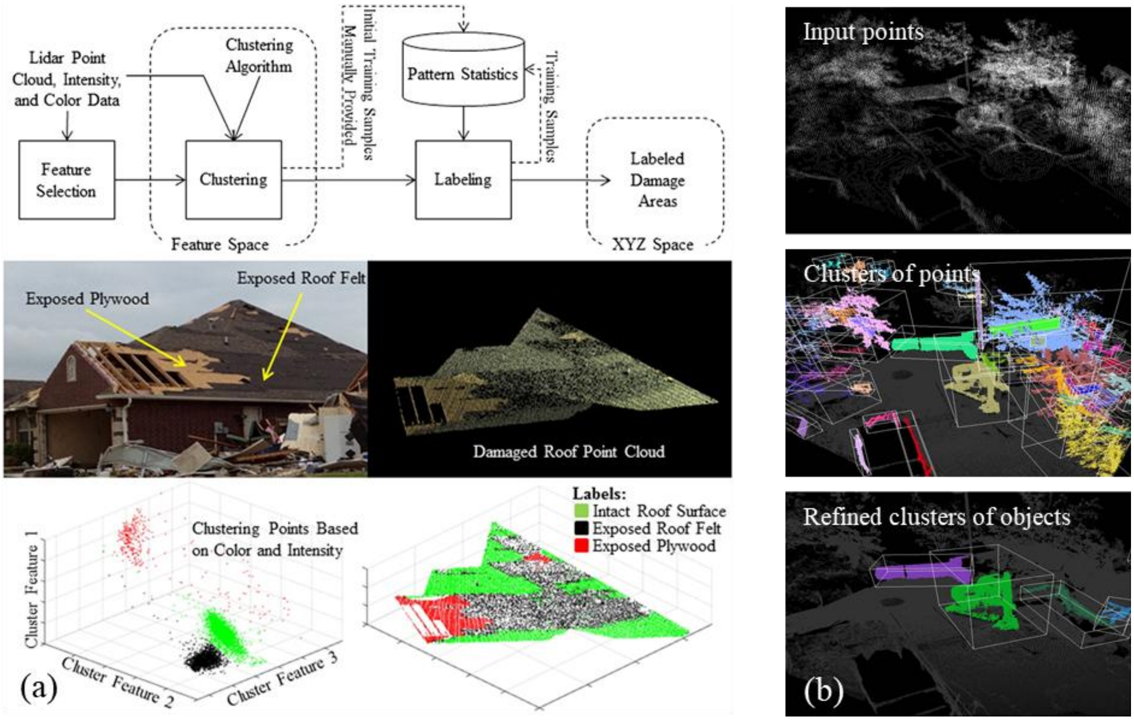


Figure 6: Unsupervised methods of pose estimation. (a) Point clusters of rooftop damages (Kashani and Graettinger 2015); (b) 3D point clusters of construction equipment (Chen et al. 2017).

## 4 DISCUSSION

Pose estimation of construction objects, as well as the digital twinning, can reflect the accurate position, orientation, and potential purposes or uses. With such information being updated in a real-time fashion, the construction site environment becomes more controllable. This is, in essence, the enabler of a smart and digital construction site. Nevertheless, each class of methods discussed above has strengths and drawbacks. Table 2 summarizes the four classes of methods in terms of pose accuracy (aggregated from precision and recall), processing time, and overall cost (including hardware and staffing cost). An ideal pose estimation method should work out a high accuracy in a short time and at a low cost. However, the reality is that there is no such method.

Table 2: Comparisons of pose estimation methods for digital twinning of construction objects.

| Class | Pose accuracy | Processing time | Overall cost | Example |
|---|---|---|---|---|
| Filtering | High | Very fast | High | Crane hoisting |
| Supervised | Medium | Fast | Medium | Safety supervision |
| Reinforcement | Medium | Slow | Low | 3D reconstruction |
| Unsupervised | Low | Fast | Low | Data pre-processing |

Table 2 shows that the filtering methods are the best in terms of accuracy and computational time, but they cost a fortune on hardware and communications. For example, an IMU-enabled IoT device costs more than US$50, and a UWB system is even higher. The reinforcement and unsupervised methods are the cheapest. However, reinforcement learning requires an in-house developed exact guiding reword function, while the unsupervised clustering results still need further processing. The supervised methods seem a balanced option. However, it requires manual labeling of the poses in the training data—which incurs additional cost. The accuracy and processing time are not acceptable in many application scenarios.

Therefore, one has to select the pose estimation methods based on their application and one's budget. It is also true for other digital twin applications in construction. If the target object is critical to the construction productivity and project delivery, for example, a tower crane or volumetric prefabricated room, then advanced sensors and filtering methods are recommended. Besides, a supervised artificial intelligence (AI) method's success should be primarily attributed not to the 'intelligence' part but to the 'artificial' part, which incurs a cost.

Furthermore, there exist three void combinations of methods and objects in Table 2. One reason is that construction equipment usually has more degrees of freedom (DoFs) than building components. For example, a mobile crane has 6 DoFs: a 3D position (x, y, z) and a 3D rotation from its chassis and the center position (x, y, z) or the equivalent (pan, tilt, length) from the jib. Human objects have even more DoFs; for instance, the human skeletal motion model in Guo et al. (2018) has 10 DoFs from the angles of the limbs, regardless of height and length. As a result, the estimation of equipment and human poses is considerably more complicated than that of building components. Plus, reinforcement and unsupervised methods are highly associated with, and thus confined to, the application scenarios, which leads to less available software libraries for the construction industry.

In the new era of AI and blockchain, new hardware and software technologies are flourishing. Some of them can be very helpful for pose estimation and the digital twinning of construction objects. For example, Birdal et al. (2018) proposed a new uniform model for detecting all quadrics, including planes, spheres, cylinders, cones, ellipsoids, and more. Novel deep learning methods, such as Luo et al. (2019), were also efficient for pose estimation and other applications such as productivity estimation with implicit poses involved. Besides, the well-known application scenarios can also be expanded by the latest means. For example, Xue et al. (2019) applied an unsupervised method to generate a similar hierarchy of point-driven urban objects, after clustering the objects' points from aerial LiDAR data like Kashani and Graettinger (2015) and Chen et al. (2017). Penzes (2018) projected multiple application scenarios of blockchain in construction, which introduced novel distributed paradigms, real-time data exchange, transparency, and trust for general applications. It can be another direction to integrate pose estimation and digital twinning for the prospect of a smart and digital construction site.

## 5 CONCLUSION

Digital twinning of construction objects is a promising research field because it is the informational foundation for smart and digital construction site and cyber-physical construction systems that can mitigate much uncertainty and ignorance in terms of construction safety and productivity. However, it is not clear to what extent many methods fit digital twinning's purposes, such as near-time responsiveness and accuracy.

This paper focuses on the pose estimation task of digital twinning and compares the pros and cons of each class of methods.

Of the proposed four-class taxonomy in this study, filtering and supervised methods are most frequently seen in the literature. The filtering methods have the best quality but also the highest cost. Although supervised methods have been significantly leveraged by recent endeavors in deep learning and big data, they can handle certain types of application scenarios. Meanwhile, reinforcement and unsupervised methods are among the cheapest, but they are complicated, closely associated with application scenarios, and sometimes require deep domain insights. Thus, the reinforcement and unsupervised methods are rarely applied to complicated (more DoFs) objects in literature. One recommended direction is to adopt the latest methods from mathematics and computer science. The other possible direction relates to the distributed paradigms, real-time data exchange, transparency, and trust that are enabled by blockchain technology.

## 6 Acknowledgments

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# SCAN-TO-BIM FOR THE SEMI-AUTOMATED GENERATION OF A MATERIAL PASSPORT FOR AN EXISTING BUILDING

**Meliha Honic[1], Iva Kovacic[2], Ildar Gilmutdinov[3], and Michael Wimmer[4]**

**Abstract:** The construction sector has a large negative impact on the environment due to its wasteful treatment of raw materials. To minimize the raw materials consumption, increasing recycling rates through reusing or recycling materials in existing stocks is of utmost importance. However, the main obstacle in the recycling of existing building stocks is the lack of information about materials incorporated in buildings.

This work presents the ongoing research within the multidisciplinary research project SCI_BIM, which received funding by the Austrian federal ministry of transport, innovation and technology. Within this paper, the semi-automated generation of an as-built BIM-Model for an existing building as well as the generation of a Material Passport (MP) is tested. In order to obtain the geometry and material information, laser scanners (geometry) and a Ground Penetrating Radar (GPR, for materials) are used. Thereby, first, a semi-automated BIM-Model is generated from the point cloud, which was obtained from the laser scans. Finally, the material information obtained from the GPR is integrated into the BIM-Model for the compilation of the MP.

First results show that the generation of the MP for the use case is possible, but confronted with manual steps, such as integrating material information from different sources (e.g. analysis of demolition experts). The results of this paper should serve as a basis for the creation of a secondary raw materials cadastre in order to enable recycling of valuable materials, thus supporting the achievement of the EU goals 20-20-20.

**Keywords:** Material Passport, Scan-to-BIM, Resources Efficiency, Urban Mining.

## 1 INTRODUCTION

The construction sector is responsible for 60% of all extracted raw materials (Bribián et al. 2011) as well as for 40% of energy-related CO2 emissions (Dean et al. 2016). There is urgent need for tools and methods for modelling and assessing the building stocks in order to generate a secondary raw materials cadastre, which could serve as basis for the realization of Urban Mining strategies. Urban Mining is promoting a systematic reuse of anthropogenic materials from urban areas, whereby in contrast to usual recycling, it

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includes, apart from mining of waste, also the exploration and observation of materials in buildings and infrastructures (Klinglmair and Fellner 2010). At present, there is a lack of knowledge on the material composition and construction of building stocks, which represents a major obstacle for realizing the Urban Mining strategy and therefore for increasing recycling rates (Brunner 2011).

For obtaining the geometry of buildings in the urban stock, in most cases laser scanning technology is used, which is already an established geometry acquisition method. In contrast to the geometry, for capturing the material composition, there is still no standardized method – which represents the main research gap: Currently there is no methodology for the comprehensive capturing and modelling of existing buildings including geometrical and material information and moreover for the semi-automated integration of materials information into a BIM-Model for the follow-up generation of a Material Passport (MP).

This paper builds up on the results of the research project SCI_BIM: Scanning and data capturing for Integrated Resources and Energy Assessment using Building Information Modelling as well as on the conference paper "BIM-supported scanning and data capturing for Integrated Resources and Energy Assessment" (Kovacic and Honic 2019), which was presented at the CIB World Building Congress 2019 in Hongkong.

The content of this paper is structured as follows. First, the state of the art regarding the scan-to-BIM process as well as a short introduction to Material Passports is provided. Second, the related research project SCI_BIM as well as the use case is described. Subsequently, the objectives and methodology are outlined. Finally, the results are presented followed by the conclusion.

## 2 State of the Art

### 2.1 Scan-to-BIM

In a typical Scan-to-BIM process, extensive human labor is required in order to generate a geometric model from an input point cloud, classify objects and establish their interrelations. There is a wide research on automation of this process, aimed to propose a framework that could at least partially reduce the need for human assistance.

While introducing semantic information into a BIM-model may require a professional engineer, geometry generation may be delegated to a computational process, as it is shown e.g. by Monszpart et al. (2015). They reconstruct an indoor scene by decomposing a scene into a set of planar primitives that constitute a regular arrangement. Namely, such arrangement, where primitives constitute of the user-specified angles between each other. Arikan et al. (2013) also generate a set of planar primitives, but is more flexible by allowing arbitrary polygons to describe a model shape. It also optimizes a model for certain criteria, but requires some human assistance to get an initial sketch of a building's geometry.

In contrast to previously mentioned works, Hong et al. (2015) and Jung et al. (2018) do not use planar reconstruction as the first step, but project the whole input cloud on a 2D plane. On a projected 2D point cloud, initial contouring is performed, followed by a regularization of contours segments. The advantage of this approach is the ability to analogously contour out other structural elements like walls and roofs, thus allowing the detection of openings like windows and doors.

### 2.2 Material Passport

Material Passports (MP) have been defined variously by different parties. BAMB (Buildings as Material Banks) (n.d.), which is a Horizon 2020 project that has been finalized in 2019, describe MPs as electronic sets of data that provide the necessary information about materials, products and components for a circular use. The independent public platform Madaster describes MPs as a digital document that records the identity of all incorporated construction materials, by analysing the products and raw materials used in a building or project (Madaster n.d.).

Honic et al. (2019) developed a method for the compilation of a BIM-based MP, which documents the material composition of buildings. Thereby the MP serves as a planning and optimization tool in early design stages with regard to the efficient use of materials and subsequent demolition.

## 3 Related research project SCI_BIM

This paper is based on the funded research project SCI_BIM: *Scanning and data capturing for Integrated Resources and Energy Assessment using Building Information Modelling*, which is conducted as collaboration of Faculties for Civil Engineering, Architecture, and Computer Science, as well as industrial partners - engineering and surveying companies 1, 2 and 3 (C1, C2 and C3). The research project is conducted on a real use case, a facility of the university, which is described in 3.1. The aim of the project is to increase both resources as well as energy efficiency through coupling of technologies and methods for capturing and modelling (as-built BIM with geometry and material composition) of buildings and assets and finally using a gamification concept for the as-built model management by users.

### 3.1 Use Case

The use case (Fig. 1) is a lab and office facility of Vienna University of Technology with a total area of 1265m², located in the 3rd district of Vienna. The use case is a single-storey building and comprises of 3 areas:  office, lab and storage area. The three areas can also be distinguished from outside due to their varying heights. At the beginning of the research project the building was still occupied by its users, which made scanning a challenging task. The users of the facility moved out one year after the project start, which enabled a comprehensive data and information gathering through further scans. Since the building will be demolished medium-term, invasive methods on walls and slabs for obtaining detailed information about the materials and verification of the actual material composition could be applied.

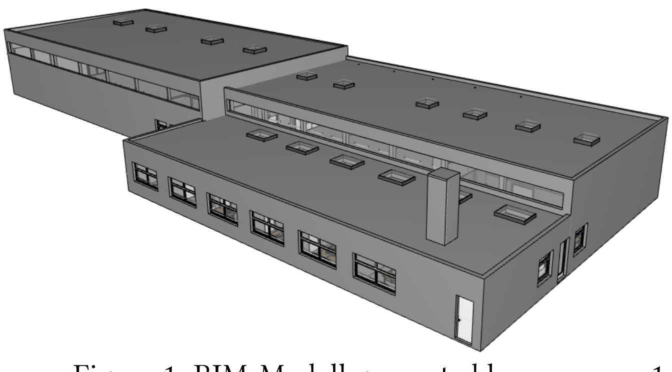

Figure 1: BIM-Modell generated by company 1.

# 4 OBJECTIVES

The main objective of this paper is to build up a methodology for the semi-automated generation of a Material Passport for an existing building. Thereby the first step is to create a BIM-Model based on the point cloud obtained from laser scanning. The second step is to integrate the information about the incorporated materials into the BIM-Model, in order to generate an information rich BIM-Model which serves as basis for the MP. The final goal is the compilation of a MP for the existing building. The method for generating the MP is based on our previous research (Honic et al. 2019), where the MP-method was used for assessing new buildings. In this paper, the existing MP-method will be optimized in order to make it applicable for existing buildings.

# 5 METHODOLOGY

## 5.1 Data acquisition

The building was scanned multiple times by three surveying companies (C1, C2 and C3 = ZAMG Archeo Prospections), which all used different devices. C1 and C2 scanned the building in order to generate a geometry model, whereas C3 was responsible for obtaining materials information of the building. C1 used a high-tech handheld laser scanner, which generates a high resolution point cloud. C2 used a TLS (TLS = terrestrial laser scanner) with lower resolution of the produced point cloud. Two different devices were used in order to test their applicability and the quality of the point clouds. However, this paper focuses on the generation of an as-built BIM based on the point cloud obtained from the high-tech handheld scanner (C1), which is why the TLS is not further discussed in this paper. The material composition of the building is investigated through using a GPR (Ground Penetrating Radar). The data acquisition with GPR could not be conducted for all elements in one, since the building was occupied at the beginning of the data acquisition phase and therefore some of the elements could not be accessed. However, a comprehensive data acquisition will be possible after the final cleaning out of the building shortly before the demolition.

The GPR uses an electromagnetic wave as a signal carrier, which is radiated into the wall by a transmitting antenna. The electromagnetic wave diffuses in the wall with a material-dependent speed and is reflected at the interfaces of individual objects or from layers of different physical properties (permittivity, conductivity). The electromagnetic signal returning to the surface is captured by a receiver antenna and recorded digitally. The changes in the signal form (amplitude and frequency) allow conclusions about the physical properties of the irradiated components, such as their mineral composition, moisture, porosity, etc. The transit time of the signal is proportional to the distance of the reflecting interface. The electromagnetic energy radiated into the walls is damped differently depending on the component (material-related absorption loss). The decrease of the amplitude of the emitted energy momentum depends essentially on the conductivity of the component and the covered distance. The conductivity is the determining factor for the effective penetration depth of the electromagnetic waves. By comparing the amplitudes (transmitter, receiver) it is possible to differentiate the areas according to their absorption properties. Thus conclusions of different materials within the building parts are possible. However, the GPR can only detect different layers due to their different densities, but cannot determine the material compositions automatically.

Therefore, an interpretation of the acquired data is necessary in order to make assumptions on the exact material composition of building elements.

## 5.2 Points to BIM

The two industrial partners C1 and C2 have generated two BIM-Models manually based on the obtained point cloud. However, a semi-automated creation of the as-built BIM was also conducted by partners of the university in order to test the automated as-built BIM generation as well as the integration of materials information into BIM. In order to generate a semi-automated BIM-Model out of the point cloud a computer-vision and image processing approach has been used. Thereby mainly the approach of Jung et al. (2018) is followed, where the core idea is detecting building objects from the projections of the cloud on a single plane. In order to obtain the heights of the three varying building parts, first a histogram that depicts the distribution of points along a certain height value, was generated. The four biggest peaks correspond to the floor and ceiling's heights of all three building parts. Based on the extracted height values, the point cloud was processed by creating sections for the points below a certain margin (current target height) and project them on a plane, thus a projection map was generated. The projection map was used for contouring in order to determine the outside contours of the building. The initial contour was detected by running the algorithm developed by Suzuki and Abe (1985) to find all closed contours on the image. Among the detected contours, the contour that included the largest floor area was selected. The resulting polyline consisted of waviness and had an excessive number of segments. In order to reduce the complexity of the polyline, curve decimation by Deuglas-Peucker algorithm was performed. After regularization of angles and detection of openings such as windows and doors through contouring, a BIM-Model was created by using the IFC format (Fig. 2). IfcOpenShell library was used which provides API between python code and IFC-file. Along the contours the exterior walls were created and its properties assigned according to the IFC Scheme. However, material properties of walls have not been assigned yet, which will be the next step, knowing that IfcOpenShell fully supports this functionality.

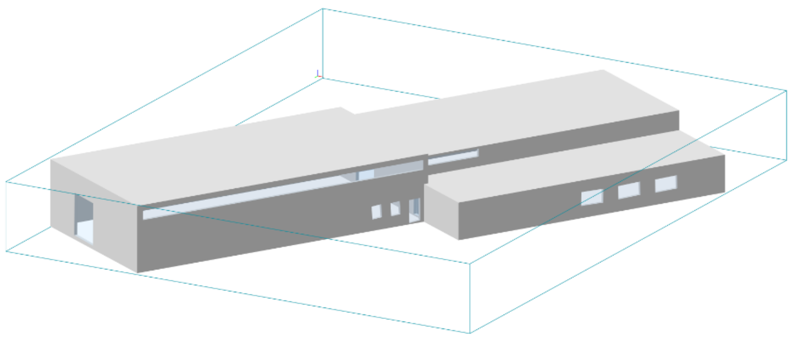

Figure 2: First result of the generated IFC-Model.

## 5.3 Material Passport (MP) – method

The applied MP-method is based on our previous research project BIMaterial: Process design for a BIM-based Material Passport, which was conducted at Vienna University of Technology. Within BIMaterial an MP-method for the assessment of the material composition, recycling potential etc. was developed for the preliminary and conceptual design stage, where the MP serves as optimization tool. The applied MP-method is based on the Austrian Institute for Building and Ecology (IBO n.d.) method, where each material is linked to a recycling grade from 1 to 5. The recycling grades are obtained from the IBO-based tool “eco2soft” (n.d.). Grade 1 stands for 75% recycling and 25% waste and 5 for 0% recycling and for 125% waste. The additional 25% in case of grade 5 is due to auxiliary materials, which are required for demolishing a building. By linking the recycling grade of a specific material to the mass of that material, the share of recycling and waste in tons is assessed. In this paper, the MP-method is applied on a real use case for the first time, where the MP serves as documentation and inventory as well as shows the recycling potential of elements. As a comprehensive data acquisition has not been conducted yet, the MP-method for the end-of-life stage is demonstrated on an outside wall and not on the entire building. Data on the volumes are obtained from the BIM-Model and the material composition from the GPR-measurements as well as from the contaminant investigation of a demolition expert.

## 6 RESULTS

Results show, that the semi-automated generation of the as-built BIM works properly, but needs further optimization. Since the building was scanned in occupied state, there is a lot of occlusion and noise that complicate the process of computer-vision procedures. Several objects became an obstacle between building and scanner, such as trees, which created holes in the point cloud. Furthermore, point clouds produce a large amount of data. In order to process the point cloud, a reduction of its size is required, sacrificing some details and precision. A further step will be the automated assignment of material information into the IFC-Model, through integration of data produced by the GPR-scans.

Since the produced IFC-model is not complete, the referential BIM-Model from C1 was used as basis for the compilation of the Material Passport. In the BIM-Model from C1 all building elements are classified via customized element IDs (e.g. AW-06 – exterior wall type 6). The material information of particular elements is coupled to the referential model via ID. 3 different wall classifications were identified: concrete (in dark grey: concrete wall type 1 and light grey: concrete wall type 2), brick (dark orange: brick wall type 1, light orange: brick wall type 2 and pink: brick wall type 3) as illustrated in Fig. 3. The MP has been created for exterior wall 06 (AW-06 in Fig. 3), thus for concrete wall type 1. The detailed composition of the exterior wall 06 was obtained from assessments of the demolition expert. Three parts of exterior wall 06 were scanned with GPR, however there are 3 parts in between which were not scanned. For the MP-assessment it is assumed that the missing parts in between are also of the same type. The total area of the wall, which is 147,5 m², is obtained from the BIM-Model. Due to its trapezoidal shape the area of the sheet has been estimated as 191,75 m² (+30% of the actual area).

Table 1 shows the input parameters, which are required to obtain the mass of all materials within the wall. The materials as well as their density, surface weight and the thickness were obtained from the analysis of the demolition expert. In Table 2, the results of the MP-assessments are illustrated. The recycling grades are obtained from IBO and changed based on the analysis results of the demolition expert. The recycling grade of the trapezoidal sheet out of steel is usually 1, as proposed by IBO. However, it was detected that the steel sheet is not fully pure such that more effort for the recycling is required as well as loss of recyclable steel sheet will occur, which is why the recycling grade has been downgraded to 3 (25% recycling and 75% waste). The insulation material is mineral wool. Results of the analysis have shown that the mineral wool contains asbestos, which is a hazardous waste and needs to be separated from the other materials. Therefore the recycling grade of mineral wool has been changed from the initial grade 3 based on IBO to 5 (0% recycling and 125% waste). The aerated concrete is not contaminated and therefore the recycling grade 2 (50% recycling 50% waste) from IBO did not need to be changed. Results show that in total the exterior wall 06 leads to about 15 tons of recyclable mass and to 16 tons of waste mass. In order to obtain results for the entire building, each element will be assessed on element-level and finally summed up to the building-level.

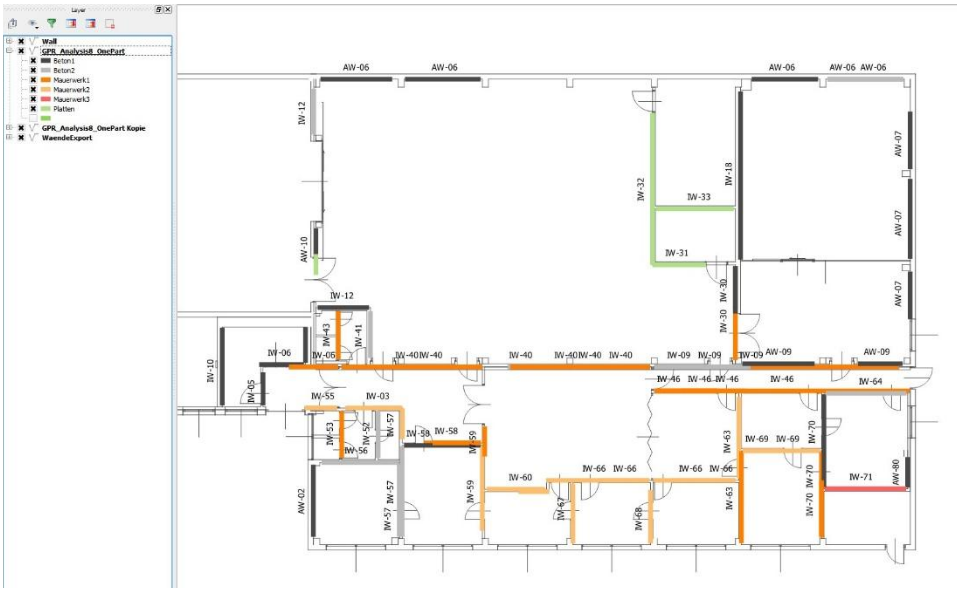


Figure 3: Material classification ©ZAMG Archeo Prospections.

Table 1: Input parameters for the MP-assessments.

| exterior wall 06 (AW-06) | density [kg/m³] | surface weight [kg/m²] | thickness [m] | area [m²] | mass [t] |
|---|---|---|---|---|---|
| trapezoidal sheet (steel) | | 10 | | 191,75 | 1,92 |
| mineral wool | 15 | | 0,05 | 147,50 | 0,11 |
| aerated concrete | 800 | | 0,25 | 147,50 | 29,50 |

Table 2: Results of the MP-assessments.

| exterior wall 06 (AW-06) | recycling grade from IBO [1-5] | analysis of the demolition expert | optimized recycling grade | share of recycling [t] | share of waste [t] |
|---|---|---|---|---|---|
| trapezoidal sheet (steel) | 1 | low purity | 3 | 0,48 | 1,44 |
| mineral wool | 3 | containing asbestos | 5 | - | 0,14 |
| aerated concrete | 2 | | 2 | 14,75 | 14,75 |
| | | | | 15,23 | 16,33 |

## 7 Conclusion

In this paper, a methodology for generating a BIM-based Material Passport for an existing building was presented. The methodology is based on coupling of digital technologies and methods for scanning and modelling an as-built BIM of a use case for further assessment of the incorporated materials. For data acquisition laser scanning and GPR-technology was used, whereby from the laser scans the geometry and from the GPR the incorporated materials of the use case were obtained. On the one hand, the as-built BIM was created manually and on the other hand, a semi-automated approach was tested, which requires further work in order to generate a complete BIM-Model. Based on the BIM-Model and analysis of the demolition expert, a Material Passport was compiled for one exterior wall, demonstrating the MP-method.

Results show that the generation of a semi-automated as built-BIM is confronted with obstacles such as occlusion and noise that complicate the process of computer-vision procedures. Several objects such as trees were also included in the scans, which created holes in the point cloud. Furthermore, point clouds produce a large amount of data, which required a reduction of its size and therefore lead to some information loss. Therefore, the manually created BIM-Model from company 1 was used for the compilation of the MP. The results of the applied MP-method on the exterior wall of the use case produced valuable results by showing e.g. the total share of recycling and waste of materials. However, the methodology is confronted with manual steps such as integrating materials information from different sources, e.g. analysis through bores on the use case by a demolition expert.

Further steps will be the optimization of the as-built BIM generation as well as the automated integration of material information into the BIM-Model. Moreover, based on the information rich BIM-Model, an automated MP should be compiled by using the bi-directionally connected tool (BuildingOne n.d.). The tool serves as database, where information on e.g. recycling potential of materials is stored as well as a calculator of the MP-results. Through the toolchain BIM – BuildingOne (n.d.) changes in the BIM-Model are synchronized and results recalculated automatically.

Since at present, there is a lack of knowledge on the material composition and construction of building stocks, representing the major obstacle for the realization of the Urban Mining strategy and therefore for the increase of recycling rates, the developed methodology could serve as basis for the creation of a secondary raw materials cadastre on city-level. The methodology, consisting of integrated assessment of geometry and materials for follow-up generation of MPs, could support the achievement of the EU goals 20-20-20 by enabling the reuse and recycling of valuable materials.

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# A BLOCKCHAIN AND SMART CONTRACT-BASED FRAMEWORK TO INCREASE TRACEABILITY OF BUILT ASSETS

**Jennifer Li[1], Mohamad Kassem[2], and Richard Watson[3]**

**Abstract:** The UK Government's review of Building Regulations and Fire Safety 2018 identified a series of failings in the construction sector including ambiguous and inconsistent regulations and standards; lack of clarity of roles and responsibilities; lack of enforcement of regulations and standards; poor product testing, labelling and marketing; inconsistent competency across the sector; and failure to address building occupants' concerns around health and safety. Traceability and the development of a digital record to provide a golden thread of information were two recommendations of the report. To address these recommendations, this paper considered the extent to which the integration of Building Information Modelling (BIM), distributed ledger technology (DLT), the Internet of Things (IoT) and smart contracts in the form of a decentralised autonomous organisation (DAO) can support enhanced traceability and the population and management of a digital record during the building maintenance phase as part of a solution to provide a platform for the digital record. A framework is proposed to bring these technological systems together creating an ecosystem that encourages digitalisation and provides traceability, better information management and compliance with regulations and standards. Further work will involve testing the framework by simulating a range of maintenance events.

**Keywords:** construction, digital record, distributed ledger technology (DLT), smart contracts, traceability.

## 1 Introduction

There were two key recommendations that came out of the UK Government-commissioned review on Building Regulations and Fire Safety (Hackitt, 2018) (herein referred to as the *Hackitt Report*) – the need for far greater traceability and a digital record to provide the golden thread of information. Traceability is concerned with the products and materials that go into buildings regarding the ability to trace those products and materials from provenance throughout their lifecycle. Adapted from Olsen and Borit (2018), traceability is defined as, "*The ability to access all required information relating to that which is under consideration, throughout its entire lifecycle, by means of recorded identifications*" (Watson et al., 2019, p. 498). A digital record to provide the golden thread of information is about producing and recording good quality information of a building from initial design intent to the current as-built state. This includes any

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decisions and changes made throughout the asset lifecycle to allow for better and safer management of that building. Recommendation 8.1 of the Hackitt Report proposes, "*Government should mandate a digital (by default) standard of record-keeping for the design, construction and during the occupation of new [higher-risk residential buildings] HRRBs. This is to include any subsequent refurbishments within those buildings*" (Hackitt, 2018, p. 104).

The Hackitt Report revealed a series of failings of the construction sector. While this is far from an exhaustive list of construction sector failings (see, for example, Farmer (2016) and Woodhead et al., (2018)), these are the failings that prompted the proposal of a mandate (Hackitt, 2018, p. 3):

1. *the roles and responsibilities of those procuring, designing, constructing and maintaining buildings are unclear;*
2. *the package of regulations and guidance (in the form of Approved Documents) can be ambiguous and inconsistent;*
3. *the processes that drive compliance with building safety requirements are weak and complex with poor record keeping and change control in too many cases;*
4. *competence across the system is patchy;*
5. *the product testing, labelling and marketing regime is opaque and insufficient; and*
6. *the voices of residents often goes [sic] unheard, even when safety issues are identified.*

These result from of lack of ability to enforce regulations and standards, fragmented processes and systems that do not ensure the health and safety of building occupants, and ambiguity and inconsistencies in documentation and roles and responsibilities.

The ability to ensure availability and access to the right information in the right format at the right time is crucial to successful operations of the construction sector. Information quality is as important as information traceability as it is the available information that drives decision-making. Raymond and Bergeron (2008) measure information quality using six items: availability, relevance, reliability, precision, comprehensiveness, and security. Jylhä and Suvanto opine that, "*if the information is poor, the actions that are based on the information are also wrong and thus have a negative impact on the value creation process*" (2015, p. 304).

The Hackitt Report that was commissioned by HM Government in response to poor quality building renovations resulting in the Grenfell Tower fire in 2017 and the 72 deaths that followed (Rice-Oxley, 2018). In addition, Christiansen (2018) identified four challenges to building maintenance as controlling costs (e.g. for energy, services, maintenance), good record keeping and data analysis, emergency response and safety, and extending the life of the asset. This study aims to consider the extent to which emerging technologies (blockchain, smart contracts and the Internet of Things) can support enhanced traceability and the population and management of a digital record during the building maintenance phase as part of a solution to provide a platform for the digital record. A framework is proposed for semi-automated maintenance and repairs of built assets during the operation stage of the lifecycle based on integration between Building Information Modelling (BIM), Internet of Things (IoT), distributed ledger technology (DLT) and smart contracts to address these problems.

Section 2 describes the technological systems considered in this paper; section 3 presents the current state of traceability in the construction sector; section 4 proposes a framework for semi-automation of maintenance and repairs during the operation of built assets; and sections 5 and 6 provide discussion and conclusions respectively.

# 2 Technological Systems for the Construction Sector

The technological systems discussed in this paper integrate to create an ecosystem that encourages traceability and better record keeping of products, services and activities that take place across the built asset lifecycle. In this context, they are conceived as "*socially constructed and society shaping systems*" consisting of "*physical artefacts; organisations; scientific components and legislative artefacts*" (van Dam, 2019, pp. 4–5). This section considers the physical artefacts as built assets equipped with sensors to provide real-time data of its conditions and the scientific components as the different information technology (IT) systems that integrate to provide an ecosystem for automated maintenance and repair activities. Organisations and legislative artefacts are considered alongside presentation of the proposed framework in section 4.

## 2.1 Distributed ledger technology (DLT)

DLT such as Blockchain, the underlying technology for the first successful cryptocurrency—Bitcoin, is a system that offers immutable and secure processing and recording of transactions that can be anything of value across a distributed, decentralised, peer-to-peer network (Li et al., 2019a). Several types of DLT are available including public, consortium and private; access can be permissioned or permissionless (Allison and Warren, 2019). DLT offers a potential storage mechanism for a digital record as proposed by the Hackitt Report and can support wider historical record keeping of built assets throughout the lifecycle.

## 2.2 Smart contracts and decentralised autonomous organisations (DAOs)

Smart contracts are pieces of computer code built on the if/then principle that self-execute and self-enforce based on pre-defined objectives and parameters (Clack et al., 2016). They can be used to increase efficiencies and traceability (Penzes, 2018). In a previous study, DLT and smart contracts were identified as drivers for new business models and organisational structures (Li et al., 2019a). One such structure is a decentralised autonomous organisation (DAO), which is an entity not managed by any one individual but by consensus of the parties setting up the DAO. Power is determined by merit calculated according to the number of tokens owned by a party and the level of trust they have within the network (Van Rijmenam and Schweitzer, 2018). A DAO is a collection of smart contracts that cannot be altered once deployed and will always operate as programmed. Therefore, ensuring the smart contracts that make up the DAO are compliant with regulations and function as intended is essential as they cannot be "turned off" once executed. Smart contracts offer the ability to automate tasks and activities throughout the built asset lifecycle whilst also acting as a mechanism to enforce compliance with regulations. The benefits of DAOs include disintermediation "under the premise that knowledge assets are codifiable and can be automated" (Sreckovic and Windsperger, 2019, p. 847), they can reduce running costs and transfer risk.

Morabito (2017) describes two types of smart contracts - deterministic and non-deterministic. A deterministic smart contract requires only the information already provided on a distributed ledger to execute (i.e. no external or additional information is required); a non-deterministic smart contract requires additional information from a trusted third party. While an aspect of DLT and smart contracts is the goal of reducing the need for intermediaries, or third parties (Li et al., 2019a), these do not need to come from human intermediaries as is often the case in the current ecosystem. This outside party is called an "oracle" and IoT-enabled devices can fulfil this capacity as is discussed in the following sub-section.

## 2.3 Internet of Things (IoT)

The interconnection of everyday objects via the use of sensors and internet connectivity is termed the Internet of Things (IoT). IoT-enabled devices are able to communicate with each other without the need for human interaction (Barnaghi et al., 2012). IoT is supporting the move toward automated systems through "*the common conception of things that are identifiable, readable, controllable, addressable, and locatable via the Internet*" (Pirbhulal et al., 2017, p. 1). IoT can provide part of the information required for a digital record for some products (particularly building services components and systems) through their use as oracles. For example, if a heating, ventilation and air conditioning (HVAC) unit has a problem and it is equipped with an IoT sensor, the sensor will collect data about the unit's problem and inform a smart contract that it requires servicing. The IoT sensor acts as an oracle providing the smart contract with only the necessary data needed to make arrangements for servicing.

## 2.4 Building Information Modelling (BIM)

The UK Government is driving the sector to adopt BIM to achieve better management of information across construction projects (UK BIM Framework, 2020). BIM is defined by BS EN ISO 19650-1 as the "*use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions*" (ISO, 2018, p. 5). BIM is the *de facto* method of managing construction projects across the built asset lifecycle, which requires a significant push to digitalise current practices across the construction sector to enable effective information sharing and collaboration where all stakeholders contribute to an "information model" continuously throughout the asset's lifecycle.

There is evidence of adoption of BIM during the design and construction phases, however, use of BIM at the operation phase of the asset lifecycle is sparse (Ghaffarianhoseini et al., 2017; Aslam and Tarmizi, 2018). The reasons for this include: organisations are reluctant to share information that is perceived as intellectual property or competitive advantage (Jylhä and Suvanto, 2015); organisations are using different software programmes raising issues of interoperability between project participants (Ghaffarianhoseini et al., 2017); use of BIM on a construction site is limited due to lack of content in the information models, lack of on-site mobile technology and lack of trained personnel (Mäki and Kerosuo, 2015); and once handover has taken place, asset owners and/or facilities managers are failing to continue using the information model with information quality cited as a key reason for this (Naghshbandi, 2016). Where work is carried out as part of maintenance and repairs of a built asset, invariably, reports, guarantees, warranties and invoices are paper based making long-term storage an issue, often with no back-up in digital form.

Each of these systems, either individually or through integration, can provide support to addressing some of the six challenges laid out by the Hackitt Report and stated above. For failing 1, implementation of smart contracts in the form of a DAO will force roles and responsibilities to be made explicit, particularly as ISO 19650 is clear in terms of roles and responsibilities for the delivery and management of building information. In addition, DLT as an immutable record has potential to drive "good behaviour". Failing 2 requires unambiguous and consistent regulations and guidance; smart contracts will require clear and concise regulations to enable effective coding and self-execution. DLT will drive better record keeping And smart contracts can support stronger compliance to ensure processes are brought in line with building safety requirements from failing 3. Failings 4 and 5 are addressed in section 4 and while the proposed framework will not address the issue around the voices of residents going unheard, failing 6, plans are in place to address this through the government's response to the findings of the Hackitt Report (Ministry of Housing, Communities and Local Government, 2020).

## 3 TRACEABILITY AND THE DIGITAL RECORD

Katenbayeva (2016) discusses the challenges of defining traceability for the sector where many definitions focus on tracking goods through a supply chain resulting in definitions on provenance and chain of custody through delivery. With lack of information traceability a key aspect of the Hackitt Report, current research on traceability at the operation stage of the built asset lifecycle is sparse. Lee et al., (2017) design Kaohsiung City Building Construction Traceability System that collects data regarding building inspections during construction to make it public for use in the event of earthquakes. However, the research is focused on the user interface of an internet-based service rather than addressing the issue of traceability in construction. Pinti et al., (2018) explore the integration of BIM and facilities management (FM) focusing on data collection, interoperable data exchange and collaboration during operation and maintenance of public administration buildings to support better information management and decision-making.

The amount of data produced during the lifecycle of a built asset is vast; currently, 96% of data goes unused and 13% of working time is spent searching for information (Snyder et al., 2018). Construction firm, FARO, has developed the concept of 'Traceable Construction' that brings together new and existing technologies to create an ecosystem that captures and processes data across the lifecycle of a built asset (FARO, 2019). Tata Steel is piloting a "traceable chain of custody" from raw material state to in-use following the life of a steel beam until it is reused or recycled (Penzes, 2018, p. 31). During the pilot, Tata Steel made data relating to the beam 'available upon request' rather than available in the public domain but each individual beam will be given a unique ID and tracked on a blockchain. Halcyon, a digital collaboration platform from Kraken IM is a world-first in blockchain-based information management that allows stakeholders to "*supply, validate and approve engineering data then creates an immutable record of that data*" providing "*a permanent digital golden thread of the information, decisions and queries made during projects*" (Kraken IM, 2020).

While much existing literature on traceability is concerned with supply chain and logistics (Katenbayeva , 2016), to encompass that which is addressed in the Hackitt Report, this study also considers traceability to include information about changes from the initial design intent to as-built state (e.g. rationale and decision-maker), manufacturer information about building components (e.g. HVAC units), installation information (e.g. when it was installed, by whom, any problems that arose during installation), scheduled maintenance and repairs/replacements (e.g. when, by whom, the process followed, any problems that arose etc.), and renovations and refurbishments.

In addition, a comprehensive definition for a digital record was devised, forthwith adapted to include services: "*A digital record provides traceability through a secure, immutable and auditable electronic record of all required information, actions and decisions taken to assess and achieve compliance of a built asset with relevant standards and regulations at a point in time. It must record stakeholder and compliance requirements, design intent, procurement of materials/components/services and construction together with the testing, validation and verification processes undertaken, capturing their outcomes in order to provide a complete decision-trail. The record will include physical asset and performance data of all components and support traceability of provenance from raw material state through manufacturing, installation, maintenance and disposal, detailing who did what, when, why, how and to what specification. The digital record must be accurate, traceable, appropriately open, non-proprietary, searchable, and show clear delineations of risk ownership*" (Watson et al., 2019, p. 498). Having the right data available can improve management, decision making and operational effectiveness; better procurement practices through increased traceability; faster response to health and safety issues; and more effective product recall.

## 4 A Proposed Framework for Semi-Automated Maintenance and Repairs of Built Assets During Operation

To address many of the problems raised in the Hackitt Report and Christinasen (2018) above, this study proposes the integration of BIM, IoT, DLT and smart contracts to automate existing processes during the operation and maintenance phase whilst simultaneously creating digital information from the outset. Automation, and production and recording of digital information will increase traceability of information for built assets at the operation phase and allow automated compilation of a proposed digital record. This integration of systems and technologies is built on the foundation proposed in Li et al., (2019b). This study extends that approach by conceptualising semi-automation of maintenance and repairs of an operational asset. Figure 1 visualises the steps taken in the semi-automated process and conceptualises how the different technological systems integrate.

The "Physical Asset" represents any built asset to which this framework could be applied. Components that make up building services systems within the built asset are fitted with IoT sensors that can detect abnormal behaviour and send a signal to the "CAFM" system. To ensure security of the process, the "DAO" is conceptualised as running on a distributed ledger, specifically, the Blockchain protocol (i.e. a linear, append only distributed ledger). The "e-Marketplace" is an automated web-based portal for managing tenders for organisations.

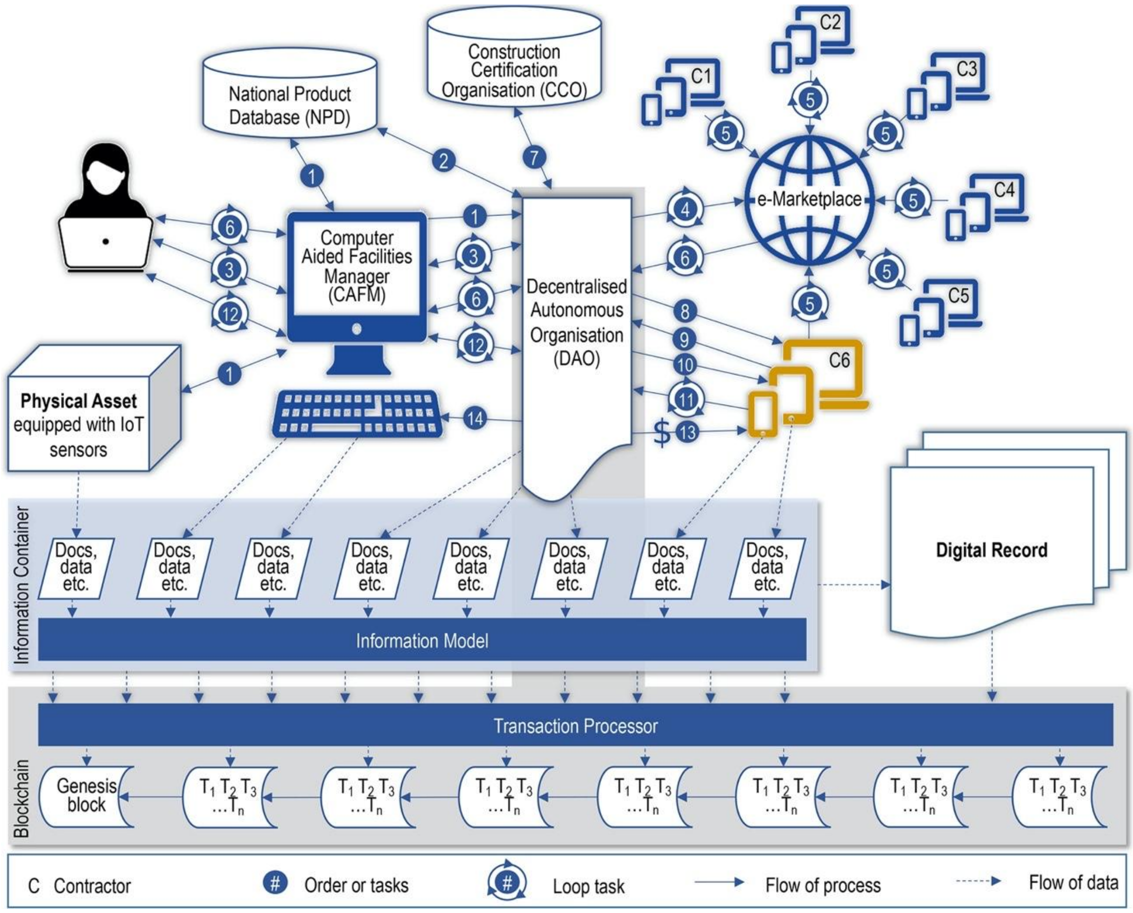


**Figure 1.** Integration of BIM, IoT, DLT and smart contracts for semi-automating maintenance and repairs during the operation of a built asset

The "Information Container" represents part of the BIM process as set out in ISO 19650 which acts as a central repository of information (e.g. information model, documents, data) for all parties involved in the project to contribute to and/or access dependent on rights access. The "e-Marketplace" is an internet-based platform that allows e-procurement of goods and services, in this instance, for maintenance and repairs. According to Costa and Grilo, e-procurement reduces 3% of public expenditure, "reduces complexity, improves competitiveness and transparency, and creates an integrated electronic environment to support advanced electronic instruments to manage, and monitor contracts" (Costa and Grilo, 2015, p. 2). Integrating e-procurement into the framework proposed in this paper can support a solution to address the failings identified in the Hackitt Report with the exception of failing 6 around residents' voices being heard.

The proposed National Product Database (NPD) is an entity that holds information about built asset components (e.g. a HVAC unit) such as: product name, classification, manufacturer, date brought to market, date removed from market, unique identifier, compliance certifications (standard, testing body, testing date, certificate number) and product characteristics. Such an entity would ensure that facilities managers have access to the most comprehensive and up-to-date information about a component and would be notified of any changes to the building standards and regulations appropriate to them. This element considers the legislative artefacts discussed in the definition of technological systems in section 2 where specific requirements relate to construction products/components. The organisation managing the NDP would need to ensure the information was kept to-to-date by the manufacturer and updated with changes to standards and regulations; the products/components linked to the CAFM system would need to share a unique identifier with those in the NPD ensuring they 'talk the same language' (e.g. they both know they are talking about "fire performance" according to the appropriate international standard). The Government's response to the Hackitt Report includes establishing a Building Safety Regulator and a "new national Construction Products regulatory role" (Ministry of Housing, Communities and Local Government, 2020, p. 12). Automating updates to standards and regulations in the NPD would ensure Facilities Managers remain compliant and can respond quickly to any changes in legislation. Creation of such an NPD supports addressing failing 5 in the Hackitt Report around the requirement for better testing, labelling and marketing of construction products whilst offering readily available traceable information.

The Construction Certification Organisation (CCO) is similar to that of the Construction Skills Certification Scheme (CSCS) (CSCS, 2020) in the UK, which is an organisation that maintains up to date records of the skills and certifications individuals hold and provides those individuals with an ID card that is linked to their account. Automating checks of individual personnel with such an organisation at the procurement phase can be directly linked to ensuring "*competence across the system*" (failing 4).

The steps taken in the semi-automated process for maintenance and repairs of built assets demonstrate how the technological systems integrate and are illustrated in the flowchart in Figure 2 which correlates to the numbered steps in Figure 1.

Maintenance and repairs can be triggered in one of four ways: via IoT sensors that detect component faults; scheduled maintenance programmed to and notified by the CAFM system; push notifications from the NDP that there is a change to standards and/or regulations; and direct notification to the CAFM system by a human (step 1). Once the maintenance/repair event has been triggered, the DAO will execute by checking with the NPD for any/all updates relating to the components to be maintained/repaired even if the trigger came from the NDP in the first place to cover changes to any other linked components/systems (step 2). The system then requests the tender criteria for the maintenance/repair job via the CAFM system (step 3), for example, time requirements, calibre and competencies of personnel, health and safety requirements, quality assurance, environmental approach and track record along with weighting to score each criterion. The DAO will compile an Invitation to Tender (ITT) request based on a pre-loaded template inputting the tender criteria from step 3. The ITT is issued automatically to the e-Marketplace by the DAO (step 4). Prospective contractors submit bids via the e-Marketplace to the DAO (step 5). The tender competition is managed by the DAO, which facilitates the bidding process scoring contractors against the tender criteria (step 6). Before a contractor is selected, the DAO will connect with the CCO to confirm the competency of the contractors meets the tender criteria confirming they are certified to complete the work (step 7). In this instance, the CCO acts as an oracle providing information that is external to the CAFM system to be processed by a non-deterministic smart contract in the DAO. If a suitable contractor is found, the DAO issues a contract to the winning contractor (conceptualised by C6 in Figure 1) and notifies unsuccessful tenderers of the result (step 8). In the event a suitable contractor is not found based on the initial tender criteria, the DAO will loop back to step 3 and request for a change in tender criteria before repeating the process until a suitable contractor is found. Upon acceptance of the contract by C6 (step 9), the DAO issues a work package order with full details for conducting the work (step 10).

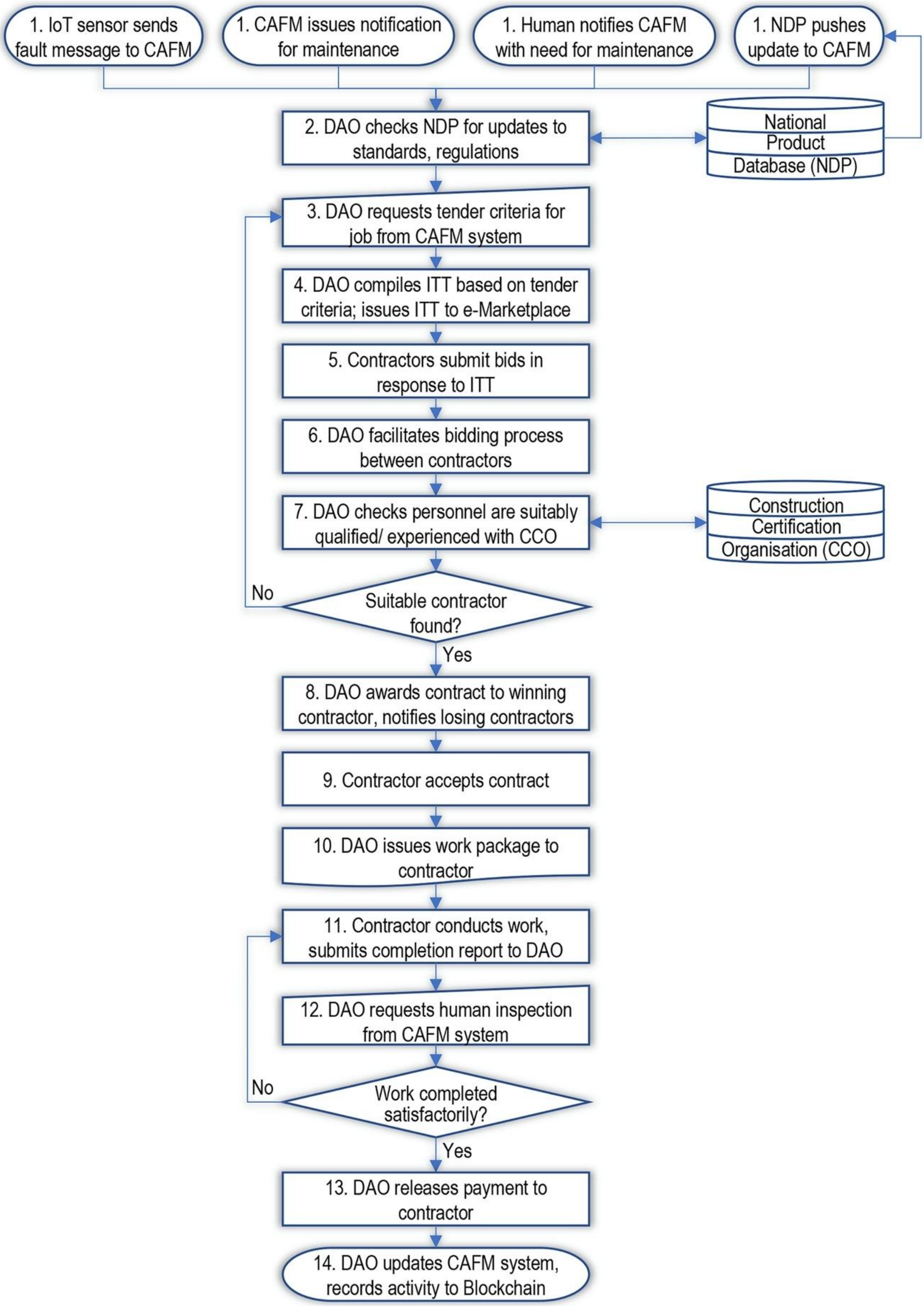


**Figure 1.** Flowchart explaining the steps taken to semi-automate maintenance and repairs during operation and repairs of built assets

C6 carries out the maintenance and repairs based on the work package instructions. Upon completion, C6 submits a completion report to the DAO (step 11). The completion report should contain details of what was done, by whom, to what standards, when, why etc. such that the digital record can be linked to the appropriate information. For example, Asset (ID 123456) was maintained to standard ID XYZ by replacing filter part (type ID 67890, instance ID ABCDEF) with part (type ID 67890, instance ID GHIJK) on 07-04-20XX, by operative (ID xxxxx) and tested for compliance using process (ID yyyyyy). The CAFM system will request human inspection where appropriate to confirm the work has been completed satisfactorily (step 12). In the event the work has not been completed satisfactorily, a rework loop begins until human interaction confirms satisfactory completion of the job. Upon confirmation that the work has been completed satisfactorily, the DAO will release payment to C6 (step 13). Finally, the DAO updates the CAFM system with the new status to reflect the changes and records traceability information about the maintenance event to the Blockchain such as that in the example above (step 14).

Throughout the process, data, certifications, schedules etc. are produced by the parties and systems involved. The items are collected in an information container and uploaded to the information model where appropriate. Depending on the requirements and the exchanges of value that take place throughout the process, specific transactions are transferred to the blockchain via a transaction processor. This may be documentation such as proof that asset components meet building regulations, financial transactions upon completion of a job, recording of decisions made during the process etc. The purpose of this is to provide immutable, chronological proof of the chain of activities that take place during the operation of the built asset whilst keeping a live version of the information model throughout the asset lifecycle. Contemporaneously, data, certification and other relevant information about the asset can be linked to the digital record, the requirements of which is to be established by Government working with industry to agree what that information will be (Recommendation 8.2 of the Hackitt Report, p. 104). Items linked to the digital record can be filtered from all information available in the information container for the relevant parties (e.g. regulatory bodies).

## 5 DISCUSSION

The framework proposed in this paper requires a number of changes across the industry for it to become a reality. It proposes the potential application of DLT and smart contracts coupled with existing technologies and processes such as BIM and IoT to revolutionise asset operation and maintenance. A number of aspects for consideration are forthwith discussed.

If the construction sector is to adopt the concept of a decentralised autonomous organisation (DAO), robust governance systems are required. As no one individual is responsible or accountable for the actions of a DAO once it is in operation it is imperative to ensure the smart contracts are coded correctly and vigorously tested before they are enacted (Van Rijmenam and Schweitzer, 2018). Kinnaird and Geipel (2018) state that DAOs "*are impervious to conventional regulation as they are stateless*" (p. 9). However, this is contrary to van Rijmenan and Schweitzer (2018) who state that, "*they must comply with regulatory requirements*" (p. 22). They also highlight that this could present a challenge when operating across borders as regulatory systems differ from one state to another. As to whether DAOs can perform better decision making than humans, further research is required. In the context of the framework proposed above, the role of the DAO is to facilitate automation rather than to challenge the regulatory environment in which it operates. However, the DAO can be used as a tool to practise and demonstrate compliance with legislation if its instructions are only to execute within the confines of the regulatory system.

The Hackitt Report's recommendation of a mandated digital record requires that it is "*open and non-proprietary with proportionate security controls*" (Hackitt, 2018, p. 104). To date, the Bitcoin Blockchain protocol is yet to be hacked but there have been successful attacks on Bitcoin exchanges which had weaknesses in their protocols (Skalex, 2017). The framework conceptualises the original Blockchain protocol for its successful history but any system that moves to integrate a distributed ledger should make an assessment of the different options available and consider what is important – privacy, security or speed. No DLT is yet able to offer a high level of privacy, security *and* speed; typically, one or the other is sacrificed (Allison and Warren, 2019). In addition, the framework does not stipulate between on- or off-chain storage. Currently, "*privacy and confidentiality are not guaranteed for on-chain transactions*" (Eberhardt and Tai, 2017, p. 2) but future developments in DLT could counteract this state.

The proposed framework moves to address some of the failings in the Hackitt Report highlighted in the introduction but recognises that DLT and smart contracts cannot support solutions to every problem or indeed as standalone systems. Failing 2 expresses ambiguous and inconsistent regulations and guidance and failing 5 is about product testing, labelling and marketing. The underlying failings are about assurance that products meet given levels of performance (e.g. through testing and compliance); that the individuals selecting products have access to appropriate and correct information (e.g. through marketing); and that the correct products are incorporated into the works (e.g. labelling). The Construction Products Regulation (CPR) 2011 (European Commission, 2020) aims to address this for products for which harmonized standards exist, requiring manufacturers to complete a 'declaration of performance' and CE mark for every product. The framework proposes creation of a National Product Database (NDP) that contains information about built asset components from raw materials to manufacturer information. This is an ambitious proposal given the effort required to establish such an entity but, once operational, it could serve as a powerful tool to support the construction sector in meeting regulations and compliance. It would link components to specific pieces of regulation and building standards and push updates when requirements for compliance change or if a product is updated, re-tested, withdrawn from sale or recalled. Each time a component is due to be maintained, the proposed system actively connects with the NDP to check for changes to regulations and standards to enable it to respond quickly and appropriately. But the NDP also pushes notifications to the CAFM system when changes to legislative artefacts are made to allow it to respond outside of scheduled maintenance periods. This way, information is always in line with the most up-to-date source.

In a similar vein, connecting to a Construction Certification Organisation (CCO) such as CSCS will ensure individuals are suitably qualified and experienced to conduct the work for which they are bidding, which addresses failing 4 concerned with competency and, in part, failing 1 concerned with roles and responsibilities. Making the individuals assigned to specific roles along with their responsibilities publicly available will hold them to account and drive establishing clearer responsibilities from the outset by encouraging a change in behaviour (Baucherel, 2020). The use of smart contracts here will drive that clarify, in this instance, through their non-deterministic behaviour and requirement for the CCO to act as an oracle providing proof of competency.

Establishing an e-procurement system (steps 3 to 7 of the proposed framework) will support addressing failing 3—weaknesses in complying with building safety requirements and poor record keeping. Inclusion of computable, machine-readable requirements into tender documents that are then cascaded into appropriate BIM artefacts (e.g. information models) or CAFM systems can be used to run performance-based checks to confirm work has been completed satisfactorily across the built asset lifecycle (Ciribini et al., 2019). Requirements for artefacts linked to the digital record and relevant information to update the CAFM system will be set out during the tender process and automatically administered by the DAO. Translating requirements into computable, performance-based metrics will promote digitisation through automatic generation of digital data that can be processed and transferred and linked to the relevant artefacts (e.g. information container, blockchain, digital record) from the outset.

In addition to addressing a number of the failings identified in the Hackitt Report, there are other benefits to the proposed framework and to automation of activities across the different stages of the built asset lifecycle. While there are many activities that can be automated (e.g. administration tasks, payments), some will not be automated until artificial intelligence is sufficiently advanced to replace the decision-making of humans (e.g. inspections), or until robotics are cost-effective enough to conduct intricate, currently time-consuming work (e.g. maintenance and repairs). Until then, simple, repetitive activities can be automated (Mason, 2017) Further expected benefits in the system include:

- Reduction in human error through automation;
- Reduction in contract administration tasks by facilities managers;
- Increased productivity;
- Automatic generation of digital data in the required format;
- Automation leading to efficiencies in the operation and maintenance of built assets;
- Reduction of transaction costs in the case of cryptocurrencies being used as payment;
- Establishing new markets and business models. The e-Marketplace could extend beyond a single asset so contractors could make offers to more than one organization or tenders from more than one organization could be aggregated. Contractors could automate bids negating the need for them to spend time manually completing bids when they could be carrying out work; and
- Development of trust and track record mechanisms (i.e. introduction of a reputation-based system) for the e-Marketplace.

Considering the current ecosystem in the construction sector, there are a number of barriers to implementation that will likely be resolved over time with technological advancement. They include:

- Limitations on technological capability (e.g. DLT scalability);
- Interoperability between systems (e-Marketplace, CAFM system, blockchain);
- Upfront costs of developing new software and hardware, integrating technological systems, development and promotion of new systems (e.g. NDP, CCO), and education and training;
- Digitalisation is required across a number of aspects before systems can be integrated (e.g. procurement, facilities management).

## 6 CONCLUSIONS

This paper has proposed a forward-thinking framework based on DLT and smart contracts to increase traceability and provide a platform for a digital record conceptualised by the semi-automation of maintenance and repairs during operation of a built asset. The framework conceptualises the establishment of two entities, a National Product Database (NDP) containing data about building components to support facilities managers with compliance with regulations and standards, and the Construction Certification Organisation (CCO) that focuses on ensuring individuals are competent to conduct the work for which they are bidding by providing confirmation that an individual has the skills, qualifications and experience required. In addition, it proposes an e-Marketplace that facilitates e-procurement to reduce complexity, improves competitiveness and transparency, and create an integrated electronic environment to support contract management.

The core aspect of the framework is a DAO that automates many of the activities in maintenance and repair, specifically, the tendering process, management of the contract post-award, facilitating approvals of work complete, facilitating payment of work on completion, and ensuring transfer of data to the information container and the Blockchain, and linking relevant information and documentation with the digital record that increases traceability over and above the current way of working. The system allows for human interaction where required, for example, in adjusting parameters for the tendering process and in approving payment for work complete.

Requirements for fulfilling the digital record are to be established by Government and industry in partnership. However, the framework ensures data produced during the operation of a built asset are collected, processed and stored in line with the requirements established in a BIM project and available on demand with proof and timestamping provided by the blockchain.

The next stage of the research will be to validate the proposed framework with industry practitioners and then test it through simulation of different maintenance activities. In addition, consideration will be given to how to mitigate the barriers to implementation.

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# AN ENCRYPTION KEY DISTRIBUTION STRATEGY FOR SECURE SHARING OF SENSITIVE INFORMATION USING BLOCKCHAIN IN CONSTRUCTION PROJECTS

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**Abstract:** Project information is shared in construction projects via centralized web-based or cloud-based platforms. However, pertaining to the distributed nature of construction projects where project participants are bound by contractual relationships for the duration of a project, a lack of complete trust among them is likely. Therefore, centralized platforms that require entrusting ownership and management of information to a single entity are unsuitable for construction projects. Therefore, public blockchain platforms that can facilitate irreversibility in records through their distributed ledger technology is recommended.

However, information on public blockchain ledgers is public which is unsuitable for sharing sensitive project information such as payment and tendering related information. Therefore, this paper proposes an encryption key distribution strategy for construction projects using which project participants can authenticate their identities and share sensitive in-formation between two contracting parties in a confidential manner. Considering the high degree of sub-contracting in construction projects and the non-technical nature of construction project participants, the proposed key distribution strategy is designed to create minimum key management overhead for the project participants. The security of the proposed key distribution strategy is validated with a symbolic attack model using a security protocol verification tool called Tamarin prover and supporting discussions.

**Keywords:** Blockchain, Cryptography, Construction Data Sharing, Key Distribution.

## 1 INTRODUCTION

In construction projects, project information is shared using centralized cloud-based or web-based platforms such as Aconex (ACONEX 2018), BIM 360 (Autodesk 2018), and PMWeb (PMWeb 2020). On such centralized platforms, the ownership of data for management is required to be entrusted with project participants or a trusted third party. Data on cloud is stored on virtual machines that share resources via a common hypervisor (Studnia et al. 2012). Therefore, risks such as data loss, data corruption, and denial of data access are some of the risks posed by centralized cloud-based platforms (Beckham 2011). Construction projects, in general, have a fragmented project-organizational structure where project participants are bound by contractual relationships for a short duration of time. Due to this reason, they do not fully trust each

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other. Therefore, a trustless method of sharing information where project participants do not have to trust each other or a centralized entity for safekeeping of information is required in construction projects. Blockchain is a peer-to-peer technology that facilitates irreversibility in records stored on them through distributed ledger technology and probabilistic consensus algorithms (Crypto51 2020, Zhang and Lee 2019). However, due to the public nature of the blockchain ledgers, they are not suitable for recording sensitive information such as payment, design changes, and tendering related information in a plain text format. Therefore, data may be encrypted with military-grade symmetric encryption algorithms such as AES (Advanced Encryption Standard) (Dobbertin et al. 2004) before storing on blockchain platforms. However, construction projects are an aggregation of contractual relationships where encryption should be done in such a way that sensitive information common between two contracting parties are accessible only by them while non-sensitive information is available publicly to other project participants for monitoring and auditing purposes. For example, sensitive information in payment claims such as personal financial information and amount paid should be kept confidential between contracting parties only. However, the fact a payment transaction has taken place between the two parties and non-sensitive information such as payment date and status should be public to facilitate transparency in payments.

In this paper, a key distribution strategy is proposed for construction projects by deploying public-key encryption (Dolev 1983) based method to share encryption keys among project participants for facilitating data confidentiality between two contracting parties and user authentication. Distribution of encryption keys in hierarchical networks such as wireless sensor networks has been explored by researchers. Researchers (Indu et al. 2016, Ali et al. 2017) have proposed key distribution methods using a trusted third party and centralized cryptographic servers between users, data owners, and cloud storage in wireless sensor networks. However, due to the fact that cloud-based key management is faced with problems of high latency (Kahvazadeh and Garcia 2018) and the requirement of entrusting central authorities with parameters of encryption, they are not appropriate for construction projects. Chen et al. (Chen et al. 2014) proposed a distributed hierarchical key distribution strategy to create common encryption keys for messaging between two sensors via a sensor cluster head. This approach requires transferring a common key to the communicating sensors via a network that may be corrupted. Diffie Hellman (DH) key exchange (Rescorla 1999) protocol facilitates the establishment of common encryption keys between two communicating parties without having to actually transfer the common encryption key over a network. However, the DH key exchange protocol approaches that do not deploy methods to authenticate the identities of honest users suffers from the vulnerability of Man-in-the-Middle (MIM) attacks (Conti et al. 2016). In MIM attacks, an attacker poses as an honest user to establish a secure communication channel between himself and another honest user and trick them into leaking sensitive information.

Therefore, the proposed key distribution strategy in this paper uses a blockchain network as a platform to authenticate the identities of honest parties interested in a confidential communication. This key distribution strategy does not require entrusting a central entity for distributing encryption keys. In the proposed approach, every project participant holds one public-private key-pair that is used to authenticate their identity as honest users and generate shared encryption keys for as many as contractual relationships necessary. Considering the high degree of sub-contracting in construction projects, the key distribution strategy is designed to create minimum key management overhead by facilitating the on-the-fly generation of shared encryption keys by users using public parameters from the blockchain platform and their own encryption key-pair. The proposed key distribution strategy is validated using a symbolic attack model that simulates attack scenarios by an adversary. A security protocol verifier tool called Tamarin prover (Basin et al. 2017a) is used to create protocol and adversary models to generate proofs demonstrating the robustness of the proposed key management strategy.

# 2 METHODOLOGY

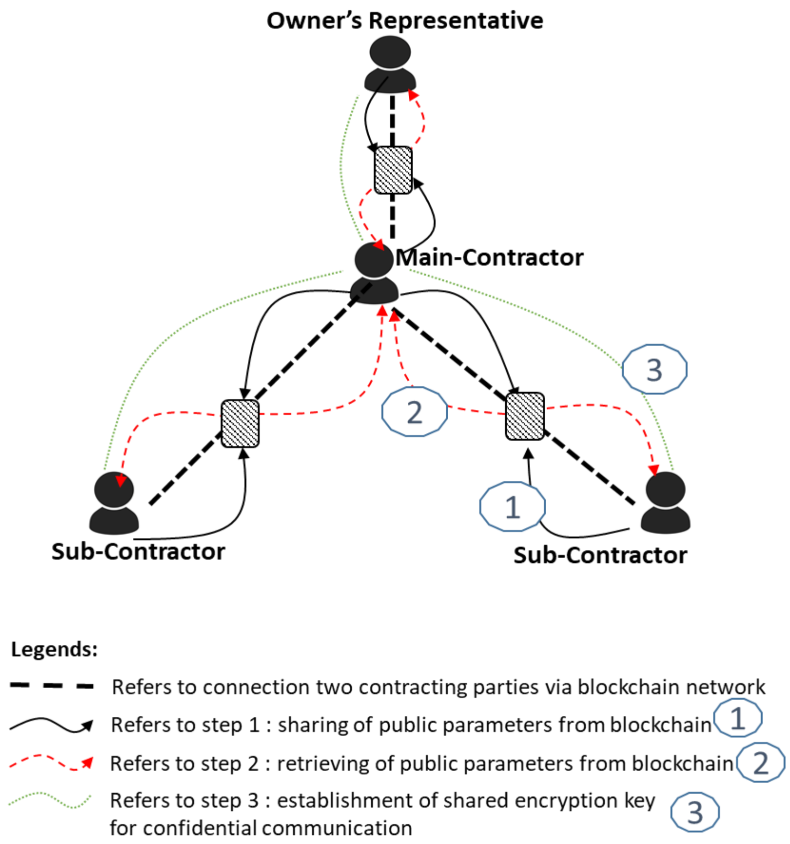


Figure 1 The System Architecture of the Proposed Key Management Strategy

In this section, the methodology of the proposed key distribution strategy for construction projects is presented. Figure 1 shows the system architecture of the proposed key distribution strategy that consists of three parts – (1) sharing of public parameters to a blockchain platform, (2) retrieving of public parameters from the blockchain platform for the generation of a shared encryption key, and (3) establishment of a shared encryption key between two parties interested in sharing confidential information. Section 2.1 introduces the components of public-key cryptography used in the proposed key distribution strategy. Section 2.2 and Section 2.3 present the methodology and the design consideration in the proposed key distribution strategy respectively.

## 2.1 Encryption for Data Confidentiality and User Authentication

Figure 2 shows two encryption primitives namely, (a) asymmetric or public-key cryptography and (b) symmetric or secret-key cryptography that facilitate security properties, user authentication and data confidentiality respectively. Encryption is defined as "the cryptographic transformation of data (called "plaintext") into a form (called "cyphertext") that conceals the data's original meaning to prevent it from being known or used. If the transformation is reversible, the corresponding reversal process is called "decryption," which is a transformation that restores encrypted data to its original state" (NIST 2015). Figure 2 (a) illustrates asymmetric encryption (Rivest et al. 1978) in which a cryptographic key pair – a public key and a private key is used, that can be used to represent and verify a user's identity. In this key pair, the public key as the name suggests can be shared with everyone whereas the private key should be kept confidential.

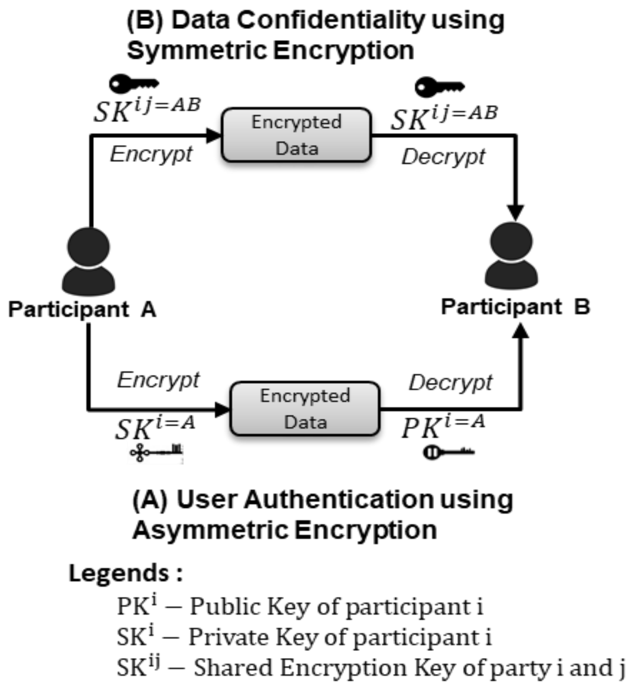


Figure 2 Asymmetric and Symmetric Encryption for User Authentication and Data Confidentiality

In order to use public-key encryption for user authentication, users should first create an asymmetric key pair ($PK^i$ and $SK^i$ as shown in Figure 2(a)) using public-key encryption algorithms such as RSA (Rivest et al. 1978). The public key consists of two random large prime numbers ($n_i$) and ($e_i$) (Rivest et al. 1978), whose public disclosure which has no effect on the security. The private key consists of an integer ($d_i$) derived from the public components by solving an NP-hard problem. The strength of asymmetric encryption lies in the fact that the private component, ($d_i$) cannot be derived from the public components, ($n_i$) and ($e_i$) through trial and error approach. For example, a 3072-bit or longer asymmetric keys will require more than 10 years to be broken through brute force as evaluated by the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce (Barker and Barker 2019).

Table 1 shows how user authentication and data confidentiality is facilitated by public-key cryptography ('m' and 'c' are plain text and cyphertext respectively in Table 1). As shown in Table 1, for user authentication, a user uses his private key to encrypt a message, more commonly known as a digital signature. This digital signature is can be verified by any public user by decrypting it with the public key of the corresponding signer, hence authenticating his identity. However, asymmetric encryption is slow and computationally expensive for encryption of large data and therefore is not used to facilitate data confidentiality (Salama et al. 2009). For data confidentiality, symmetric encryption such as AES (Advanced Encryption Standard) (Dobbertin et al. 2004) that uses a single encryption key for both encryption and decryption as illustrated in Figure 2 (b), is used. The robustness of asymmetric and symmetric encryption for user authentication and data confidentiality can be found in well-established standards for encryption (Barker and Barker 2019). Therefore, this paper uses asymmetric and symmetric encryption primitives for user authentication and data confidentiality in the proposed key distribution strategy for construction projects.

Table 1 Public Key Encryption (Rivest et al. 1978)

| | Encryption | Decryption |
|---|---|---|
| Data Confidentiality | $c = (m)^{e_i} mod(n_i)$ | $m = (c)^{d_i} mod(n_i)$ |
| User Authentication | $c = (m)^{d_i} mod(n_i)$ | $m = (c)^{e_i} mod(n_i)$ |

## 2.2 The Proposed Key Distribution Strategy

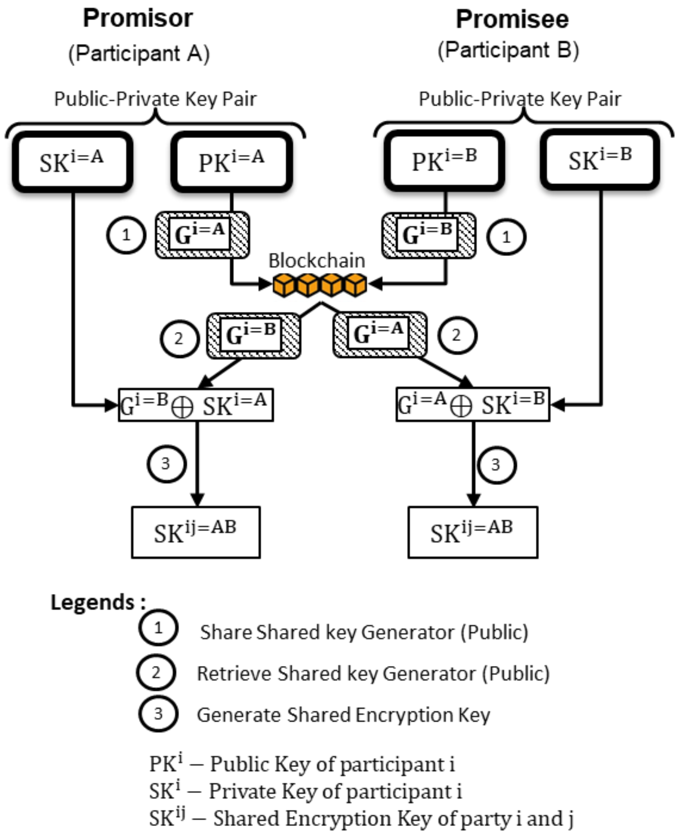


Figure 3 The Proposed Key Distribution Strategy

This section presents the proposed key distribution strategy based on the Diffie-Hellman Key (DH) exchange method (Rescorla 1999), and public-key cryptography standards such as RSA cryptography (Rivest et al. 1978) and Blockchain technology. The methodology as illustrated in Figure 3 consists of three steps – (1) sharing of a shared key generator to a blockchain platform, (2) retrieving of the shared key generator from the blockchain platform, and (3) establishment of a shared encryption key between two contracting parties. As shown in Figure 3, the contracting parties consist of a promisor (one who promises to pay and is on a higher level in the project organizational hierarchy) and a promisee (one who is entitled to a payment upon completing work and is relatively lower on the project organizational hierarchy) such as a main-contractor and a sub-contractor respectively (as shown in Figure 1).

In this first step, as shown in Figure 3, two contracting parties who are interested in establishing a secure channel for sharing confidential information create generators, $G^{i=A} = (e_A)^{d_A} \bmod(n_A)$ and $G^{i=B} = (e_A)^{d_B} \bmod(n_A)$ each (where $e_A$ and $n_A$ are the public key parameters of the promisor) and share it on a blockchain platform. Once the generators are shared on the blockchain platform, the relevant parties confirm the authenticity of those generators through other channels of communication such as email (discussed further in Section 2.3). In the second step, as shown in Figure 3, the project participants download each other shared key generators. Smart contracts may be deployed for uploading and downloading customized information (such as generators in this case) from blockchain platforms (Ahmadisheykhsarmast and Sonmez 2018, Regnath 2018). In the third step, as shown in Figure 3, a shared encryption key is established between the two participants (promisee and promisor). Both the participants A and B generate a common encryption key, $SK^{ij=AB}$ (as shown in Figure 3) by using their own private keys and shared public parameters such that $SK^{ij=AB} = (G_{i=B})^{d_{i=A}} \bmod(n_A)$ and $SK^{ij=AB} = (G_{i=A})^{d_{i=B}} \bmod(n_A)$.

## 2.3 Reduction in Key Management Overhead

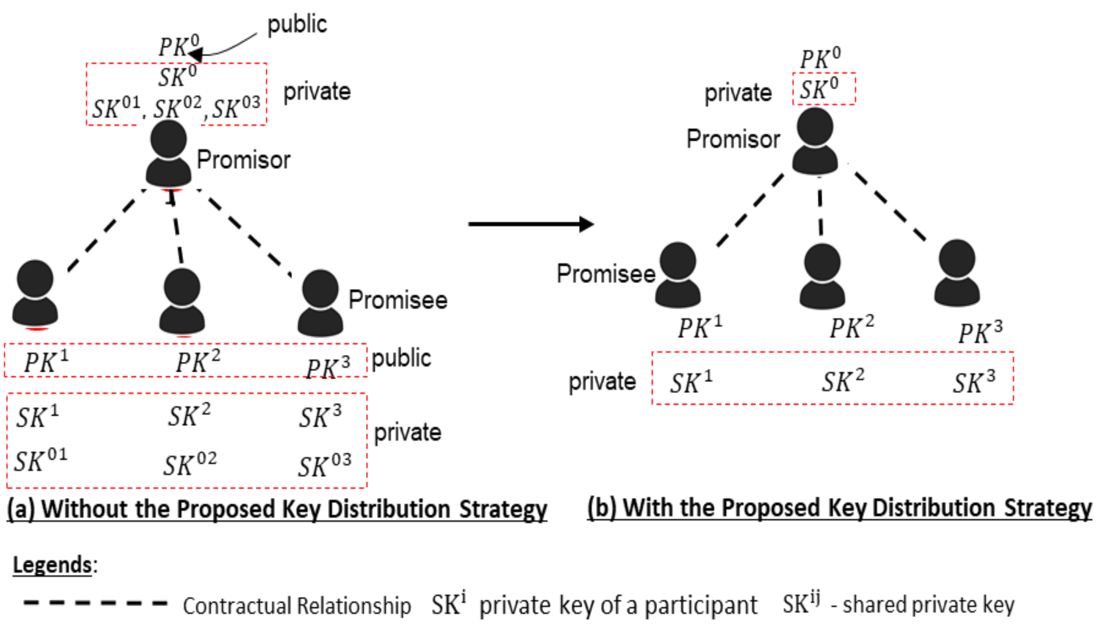


Figure 4 Shared key distribution with and without the proposed key distribution strategy

Figure 4 shows a scenario of shared key distribution between two contracting parties with and without the design considerations of the proposed key management strategy.

Figure 4 (a) shows a case where shared keys are distributed using other methods such as using encryption to protect keys when being transferred through a network. In such cases, due to the hierarchical organizational structure of construction projects with a high degree of sub-contracting, every project participant will have n+1 number of private keys to manage, where n is the number of contractual relationships of a project participant. As shown in Figure 4 (a), the proposed approach reduces the key management overhead to one key per to one per project participant. Furthermore, there may be additional keys to manage if encryption is used to secure key transfer. Therefore, the proposed key distribution strategy provides a method that is unaffected by the security of a network (demonstrated in Section 3) to distribute shared encryption keys. In the proposed approach, shared encryption keys or private keys are never exchanged over a network and therefore, the security of the proposed strategy does not depend on the security of the network.

## 3 VALIDATION

In this section the security of the proposed key distribution strategy is assessed for two cases – (a) leaking of private keys to an adversary and (b) an adversary posing as an honest user (as shown in Figure 5). Tamarin prover (Basin 2017b), a security protocol verifier tool is used to deploy a symbolic attack model to validate the security of the proposed key management strategy under the cases shown in Figure 5. Tamarin prover has been widely used by researchers for the verification of security protocols (Basin et al. 2015, Dreier et al. 2018). It provides a first-order logic-based modelling language and uses equational reasoning with heuristics for verification and falsification of a symbolic attack model. A protocol model and adversary models may be developed using the constructs, “rule” and “lemma” of the tamarin modelling language followed by the deployment of the tamarin prover engine to validate the protocol against the adversary models. The results prove robustness or security loopholes in a cryptographic protocol.

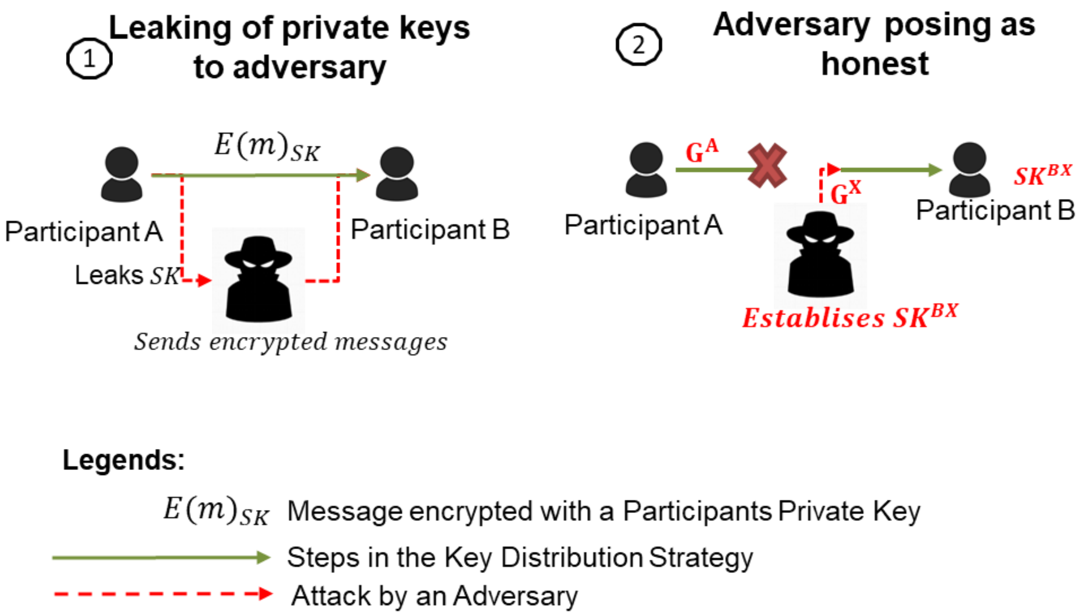


Figure 5 Illustration of Cased of Security Vulnerabilities

Figure 5 (1) shows the case in which an adversary controlling the network can steal private keys during key distribution through the proposed key distribution strategy. Figure 5 (2) shows the case where an adversary poses as an honest user and establishes a shared encryption key to communicate with another honest user and then tricking him into leaking sensitive information. These two cases are modelled using the Tamarin modelling language as shown in Figure 6(b) and Figure 6(c) respectively. The protocol model of the proposed key distribution strategy is shown in Figure 6(a).

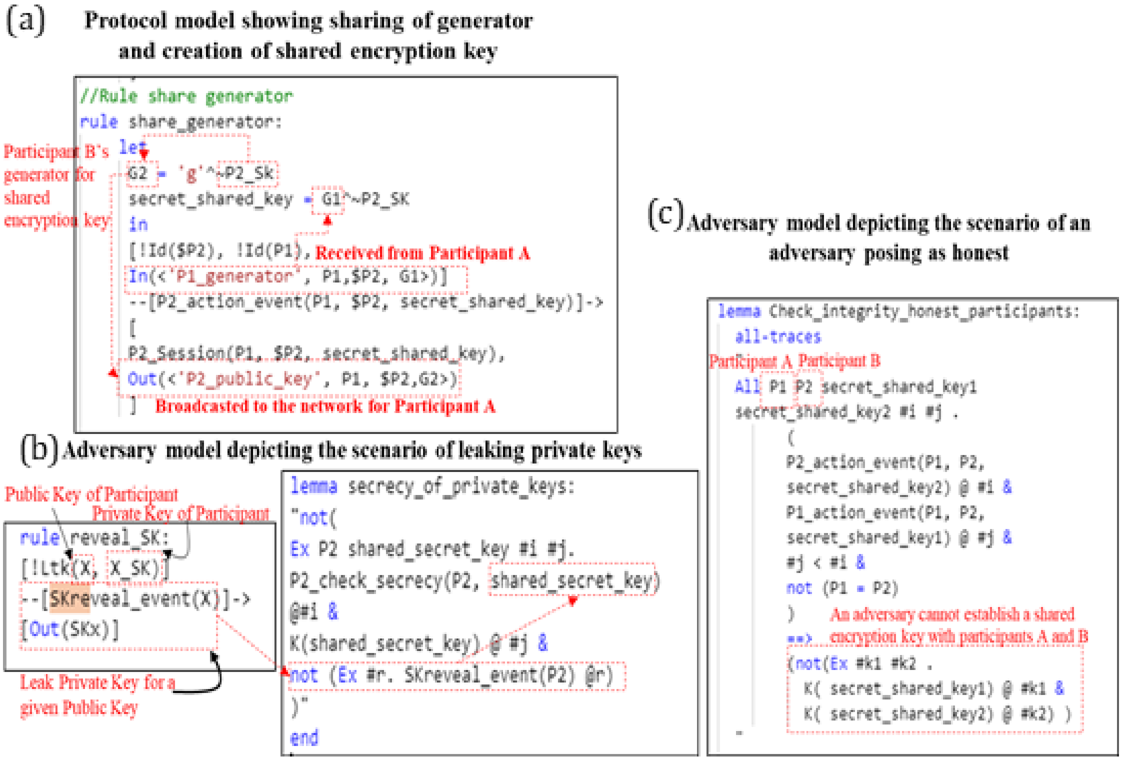


Figure 6 Protocol and Adversary Modelling using Tamarin Prover

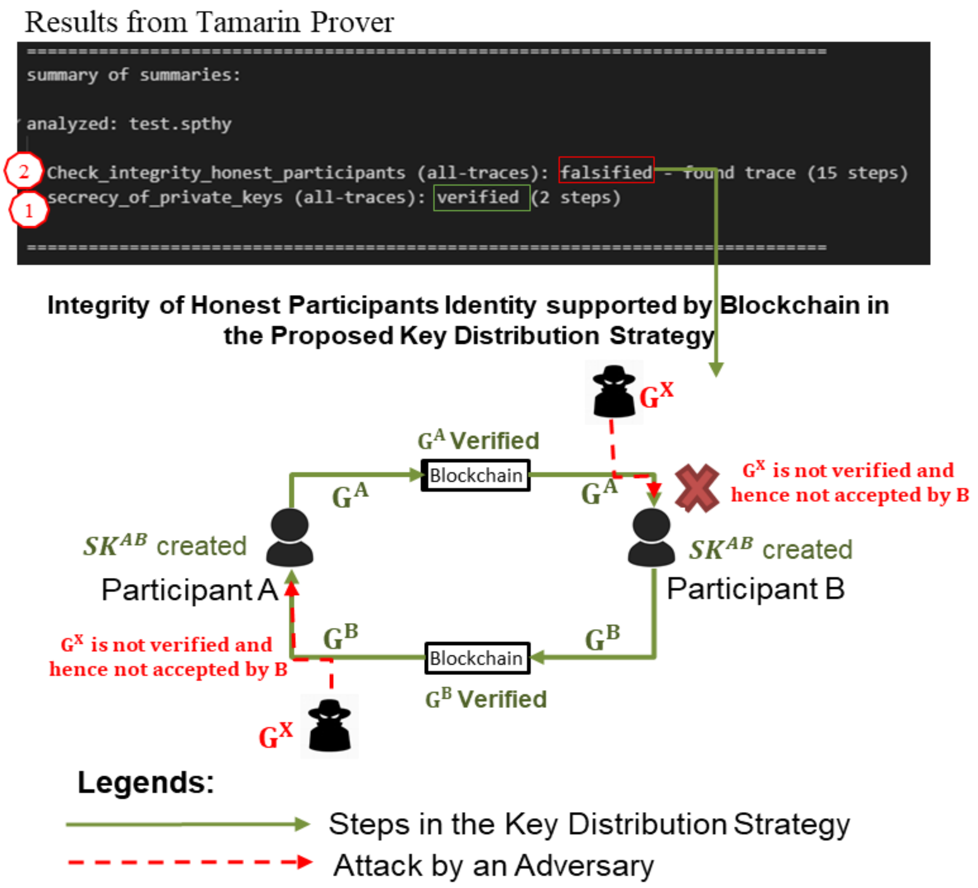


Figure 7 Results from tamarin prover and discussion

Figure 7 shows the results of the execution of the symbolic attack model using Tamarin prover. The results show that the proposed key distribution strategy, at no given point, leaks private key information to any adversary, unless it is purposefully leaked out by a participant (or stolen). This means that the proposed key distribution strategy is suitable for establishing shared encryption keys in compromised networks. Hence as discussed in Section 2.3, it provides the benefit of low-key management overhead with high security.

The results (as shown in Figure 7), however, shows that the proposed key distribution strategy is not resilient to the second security vulnerability scenario where an attacker poses as an honest user. This is because the protocol model (as shown in Figure 6) does not consider the security of identity verification provided by the blockchain platform. The proposed key distribution strategy deploys blockchain's property of immutability for verifying the authenticity of the key generators (as discussed in Section 2.3) by the respective participants. Therefore, as shown in Figure 7, any attempt by adversaries to intercept honest communication and inject his own key generators to establish a shared encryption key to communicate with honest users is prevented by the honest users (in contrary to the corresponding case shown in Figure 5(2)).

## 4 Conclusion

Construction projects consist of project participants who are bound by contractual relationships. Although it may be favourable to share project information among all project participants to facilitate transparency and hence smooth project execution, some sensitive information is required to be kept confidential between contracting parties. Therefore, this paper presents an encryption key distribution strategy for sharing sensitive information using public blockchain platforms. The proposed key distribution strategy facilitates user authentication and confidential information sharing between two contracting parties with minimum key management overhead. The robustness of the key management strategy is demonstrated through a symbolic attack model and the results are discussed. The security of the proposed key management strategy for some cases, however, depends on the choice of the blockchain platform. It is designed to be deployed using large public blockchain platforms that have a network size of 8000~10000 nodes and use probabilistic consensus algorithms such as PoW (Proof-of-Work) and PoS (Proof-of-Stake) as in Bitcoin and Ethereum blockchain platforms. Such blockchain platforms facilitate high security in terms of the irreversibility of records which is required by the proposed key distribution strategy. Smaller public blockchain platforms and permissioned blockchain platforms, however, may not be able to provide high immutability compared to large public blockchain platforms due to low total network computational power and use of deterministic consensus algorithms respectively. However, the architecture of permissioned blockchains is preferred and being investigated for private organizations. Therefore, in the future, the proposed key distribution strategy will be extended with additional security measures for using permissioned blockchain platforms. The additional parameters of security that should be deployed to address various security threats on permissioned blockchain platforms for construction projects will be explored in the future.

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# IMPROVING SITE ACCESS VERIFICATION AND OPERATOR SAFETY IN SMART AND SUSTAINABLE ASSETS: A PILOT STUDY IN A UK DECARBONISATION PROJECT

**James Wakefield[1], and Mohamad Kassem[2]**

**Abstract:** The built environment is increasingly shifting towards smart and sustainable cities. This transformation is accompanied by the implementation of new digital and smart technologies, and their supporting infrastructure. This advancement poses new challenges to the process of operating the built environment and in particular, to the management of new risks associated with use and operation of a more complex built environment. There is still a dearth of studies proposing new ways to cope with risks from the increased sophistication in the built environment.

This paper analyses the ability of an emerging technology and process for site access verification. The aim is to improve control measures in respect of the operational risk profile. HyDeploy, a UK based sustainable built environment gas decarbonisation pilot project, is used as a study case. HyDeploy is a project aiming to demonstrate that using hydrogen blended gas for heating and cooking is just as safe and convenient as the gas used currently in the UK.

The paper presents the current process for site access verification used in the project, before investigating the potential benefits of the application of an emerging technology for site access procedure. The paper concludes that the emerging procedure has the potential to improve both the compliance position of site owners, and the overall operator safety on site.

**Keywords:** Smart Cities, Compliance, Asset Lifecycle Operation, Health and Safety, Site Access Verification, Individualised Training Experiences

## 1 INTRODUCTION

The emerging challenges associated with growth in population and urbanisation are in part addressed by solutions for the digitalisation of the urban environment (Heaton and Parlikad 2019). Rapid urbanisation trends in the period up to 2027 requires investments up to $78 trillion in global infrastructure (PricewaterhouseCoopers, 2017). Global warming is a key area of concerns where digitalisation of the urban environments is part of an effort to decarbonise energy consumption. Tools that can predict potential faults with infrastructure, to intelligent design of built environments that can filter air pollutants, technology has a promising role in improving built environments (Ahmed et al., 2017). Many cities are increasingly referred to as smart cities, with the city being

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"smart" meaning that "actors as multiple stakeholders (or societal initiatives guiding these actors) aim for sustainable solutions adopting digitalisation and other technological advancements" (Öberg, Graham and Hennelly 2017, P. 470).

Regardless of the drivers for the digitalisation of the urban environment - be they sociological, economical or ecological - hardware that supports increasingly digitised urban environments will be required to be safely and efficiently maintained according to the regulatory frameworks and the business models of the day. In such a context, this paper examines a specific use case about access verification and operator safety in a decarbonisation project using hydrogen blended gas for heating and cooking.

## 2 Literature Review

Workforce health and safety (H&S) in the construction sector (that being the sector responsible for delivering the future built environment) is a global concern. The construction sector has one of the highest fatal injury rates in both the developed and the developing world (Kassem et al., 2017). Efforts to improve the H&S performance of the construction sector are plentiful and until recently studies have largely focused on H&S issues on the construction site. However, facilities management and in particular the operation and maintenance of the existing built environment has a much higher rate of injury and illness when compared to all other fields of employment (Wetzel and Thabet, 2018). Tools and workflow enabled by Building Information Modelling (BIM) have the potential to support the transfer of hazard mitigation and safety data to operatives involved in assets operation and maintenance (Wetzel and Thabet, 2018). Carbonari, Stravoravdis & Gausden (2018) assert that building information models can be exploited to support the delivery of more efficient facilities management services. Despite the recognised benefits of BIM in supporting workforce H&S, the current adoption of BIM in the operational phase of asset is minimal in comparison to the design and construction phases (Hilal, Maqsood & Abdekhodaee, 2019).

H&S training is key to improve the safety of workforce at all stages of an asset life cycle. There are many opportunities to exploit the potential of e-learning and associated digital learning technologies as a mechanism for delivery of hazard related information and training. Construction safety training delivered via an e-learning mode resulted in increased safety standards when compared to construction safety training delivered in the traditional space (Ho and Dzeng, 2010). The overall performance of computer-aided technologies to deliver construction site safety training is superior in several technical aspects compared to traditional tools, specifically, representing actual workplace situations, providing text-free inter-faces, and eliciting better user engagement (Gao, Gonzalez and Yiu, 2019). Other recognisable benefits of computer aided technologies specifically for construction include the ability of e-learning to support effective health and safety training delivery in a range of languages (Williams et al., 2010). According to Blocker (2005), e-Learning has the potential to address operational issues such as reducing costs, providing greater access to information and accountability for learning, and increasing employee competence and competitive agility. There is however much debate about factors affecting quality of e-learning outcomes. Ertmer & Newby (2013) assert that many instructional designers are operating with limited pedagogical knowledge and designers must understand the position of the practitioner in order to be able to accurately design effective materials.

Highly engaging types of safety training can have a positive impact on safety performance (Shamsudin, 2018). To be effective the training must include content that is relevant to the trainee lives (Aik and Tway, 2006). Such understanding also informs efforts to leverage technology to provide short relevant training content at a time when it is most relevant to the task in hand, so called micro credentials (or credentialing). Such a training approach offers the opportunity to disrupt the time-based education and training model and recognises the competence required for tasks that are directly related to employment (Harvey, 2018). One such example of the application of micro credential training in the facilities management domain in presented in this paper. In this application, specific competencies of contractor employees are leveraged as credentials for site access in the HyDeploy project at Keele University in the UK.

## 3 Case Study

HyDeploy is a UK energy decarbonisation demonstrator project which is designed to demonstrate for the first time that a blend of hydrogen and natural gas can be distributed and utilised safely and efficiently in the UK distribution network without disruptive changes for consumers.

The 10 month project involves blending up to 20% hydrogen into the Keele University gas network, delivering low carbon heat to customers without requiring disruptive and expensive changes in their homes. In addition to demonstrating the feasibility of the specific technology the project enables key stakeholders including the UK Government, public safety experts, the energy industry and academia to develop and understand the science base, the regulatory position, the supply chain and customer perceptions of hydrogen as a decarbonising element of the energy system. These insights are key to understand the wider process of feasibility testing and subsequently the adoption of energy decarbonising projects of all types.

Under the UK Climate Change Act, the UK must reduce its carbon emissions to net zero by 2050. Over a third of UK carbon emissions are from heat, with little progress having been made in decarbonising this sector to date. Over 23 million UK households (83%) are connected to a gas supply and with gas being a flexible and convenient way to deliver heat, a key challenge is to reduce gas carbon content. Unlike natural gas, when hydrogen is burned it does not produce carbon dioxide. The hydrogen used for the project is produced by an onsite electrolyser (supplied by renewable electricity) which splits water into oxygen and hydrogen before blending the hydrogen into the Keele University gas network. This means that in general terms a blend including 15% hydrogen would have a 15% decarbonising effect.

Keele University was selected as the home for HyDeploy and a number of other smart energy research projects on account of the Keele University campus being representative of a small town; this is in terms of its population demographics, its land mass, and land usage. The campus incorporates 101 residential buildings, 8 multi-residential buildings, 17 extensive office blocks and laboratories and 7 recreational and service facilities. Keele University owns the utilities infrastructure (including the gas network) and as such is a licenced transporter and carrier of gas. Keele University campus then is an ideal provider of a “living laboratory” for smart energy projects such as this one.

UK Gas Safety (Management) Regulations (GS(M)R) govern gas transportation and supply in the UK. In order that a hydrogen blend gas can be transported across and within any part of the UK gas grid, a specific exemption to the GS(M)R is required, this can only be granted by the UK Health and Safety Executive (HSE). Exemptions are permissible only if the health and safety of persons likely to be affected will not be prejudiced by the change process, with the change process on this case being the introduction of the hydrogen blend to the grid.

Permission for the pilot was granted by the UK HSE on the basis of extensive pre pilot project research and testing by the UK Health and Safety Laboratory (HSL) in partnership with Keele University and a number of commercial partners (including the UKs biggest gas distributor Cadent) which demonstrated that a 20% blend of hydrogen by volume is as safe as natural gas. The scope for the pre pilot project research and testing included (but not exclusively); network materials assessments, appliance and installations, [blended] gas characteristics and detection, and emergencies and maintenance procedures.

Due to innovative nature of this project and the likely H&S risks to be involved, a number of specific site access verification arrangements (SAV) were specified for personnel (owner employed and contractor) responsible for the operation and maintenance of the network for the entire duration of the project. These HyDeploy specific SAV arrangements were implemented as part of a two-tier approach with Tier 1 being the existing general SAV control arrangements for the estate (tier one), and tier two being the HyDeploy specific SAV arrangements. The scope for this paper covers both tiers of access but is principally concerned with tier two, SAV arrangements, specifically for gas network engineers of first line contractors responsible for attending gas emergencies and carrying out meter works.

## 4 RESEARCH METHODS

A three stage qualitative content analysis approach was adopted to analyse data obtained from two research participants, identified via a purposeful sampling method. The participants represented the expert position on the estate owner side (Principal Mechanical Engineer for Keele University) and the contractor side (Future Networks Manager for Cadent Gas Ltd) respectively. Both participants have been extensively involved in the HyDeploy project since inception and as key members of the consortium stakeholder group have been instrumental in the development and implementation of the existing HyDeploy SAV control process.

It was identified that first hand insight would be required; this stage then was designed to ensure that the existing SAV arrangements reported by the researcher were an accurate representation of the SAV protocols which have been adopted for the project. Both participants took part in a semi structured interview process, Figure 1: Existing HyDeploy Cadent Operative Specific SAV Control Criteria was outputted as a result of this stage. Following an initial feedback opportunity both participants agreed that Figure 1 is an accurate representation of the SAV protocols which have been adopted for the contractor group.

Subsequent to formalising the Existing HyDeploy Cadent Operative Specific SAV Control Criteria flow, both participants completed an open-ended questionnaire which was designed to establish the degree of confidence on the part of the estates and the contractor representatives in the agreed Existing HyDeploy Cadent Operative Specific SAV Control Arrangement. The questionnaire also invited the research participants to identify and comment upon perceived opportunities to develop the SAV Control Arrangements for the contractor group. This component is undertaken with the benefit of two months prior live operation of the HyDeploy project and associated systems and procedures.

Prior to completion of stage three open-ended questionnaire, the researcher shared Figure 2: Proposed Site Access Verification (SAV) Control Criteria Flow with both research participants. Figure 2 along with supporting information demonstrates a representative workflow that can be enabled with the application of new technology that can improve the H&S of operatives and the H&S compliance of the main contractor. Supporting information assisted the research participants in assessing and commenting upon that which is being presented. The general principle underpinning the proposed technology is the ability to provide operatives web-enabled access to information that is pertinent to the job being undertaken at any given time. This process can be linked to a range of required outcomes, such as the cultural proposition (public messaging), the efficiency position (how to do this job most efficiently), but the main focus of this study in on Health and Safety Compliance (risk mitigation).

# 5 Research Findings

As the network maintenance supplier to the Keele University HyDeploy gas network Cadent are contractually obliged to ensure that a team of compliant service engineers is available 24 hours per day, 7 days per week, 365 days per year to attend to gas emergencies and meter works on the estate. Cadent determined an operational requirement that a team of 100 engineers would therefore need to be trained to meet HyDeploy Cadent Operative Specific SAV Control Criteria (tier two) in order to ensure compliance for access. The compliant status of the operative is then recorded back to the Cadent job scheduling system to ensure that only compliant operatives are available to be scheduled for works at the Keele University site. This represents a change in operational process for Cadent in that operative allocation to a job is ordinarily governed by job role qualification and the regional allocation of the operator. It is now the case that job allocation will controlled by the additional HyDeploy Cadent Operative Specific SAV Control Criteria in addition to Existing General Estate SAV Control Criteria.

## 5.1 Understanding existing (pre HyDeploy) operative general estate SAV control criteria

The Keele Estate is an open access site, this means that SAV comes with additional challenges over those expected to be encountered on a closed (gated) site such as defence facility or office block.

The general (existing) SAV Control Criteria are based upon an approved contractor scheme, meaning that baseline health and safety training checks as well as, finance, insurances and other checks are made. The basic credentials required to be met by an operative (employed or contracted) in order to gain access to the site are largely undertaken at an operational level by the contractor, with much of the processing ordinarily handled by the appropriate qualified person on behalf of the contractor (usually not the operative). These credentials are classified as Stage One existing Keele Estate General Site Access Verification Control Criteria and the data pertaining to the completion of such are attributes of the contractor organisation (or the department in the case of an estate employee). In order to meet the SAV control criteria for stage one the contractor operative presenting for work will satisfy the following criteria:

- Employed by an approved Keele contractor,
- Approved Risk Assessments and Method Statements (RAMS) assigned to the job,

- Approved work place safety plan will have been completed, and
- Approved applications for any and all required permits to work.

Assuming the stage one Existing General Estate SAV Control contractor (or estate employee) attributable criteria are verified as having been met, the operative is now ready to present for site access approval (stage two) at the university estates reception. It is exclusively the responsibility of the operative as an employee of a verified contractor (or employee of the estate), to have completed the Keele Estates Induction and Knowledge Check pertaining to general estate access prior to being granted access to the site. Data pertaining to the completion of this induction then is an attribute of the operative. The Keele Estates Induction is presented in the form of a training video with audio, followed by a written knowledge check. The Estates Induction is undertaken in the Keele estates building prior to first estate access and is valid for a period of 12 months post completion. Upon expiry of the Estates Induction and prior to being granted further estate access, the operative will be required to refresh the training. Completion records and expiry data are stored by the Keele Estates operations team.

Further to Existing General Estate SAV Control Arrangements there are occasions where site within site (sub sites) do exist, this is most commonly the case when a capital construction project is being undertaken, such as the construction and installation of the on-site electrolyser supplying hydrogen to the gas network for the duration of the HyDeploy project. Where sub sites do exist the principle contractor will take responsibility for the activities (including SAV arrangements) up until the point when the project is handed over to Keele University (i.e when the capital phase on the sub site is completed). Before satisfying SAV Control Arrangements for a sub site, the operative would first need to satisfy Existing General Estate SAV Control Criteria.

## 5.2 Understanding first line contractor gas network engineers SAV control arrangements specifically for Keele HyDeploy

The project consortium recognises the vital importance of public safety. Due to the complex nature of the project meant it was necessary for the consortium lead to seek regulatory exemptions from the UK HSE in the planning stage. Following a six-month review and consultation period in collaboration with all consortium partners including the UK HSL, regulatory exemption was granted by the UK HSE.

As part of the pre project safety review by the HSL, over 200 emergency and scheduled maintenance procedures were assessed, the findings of which resulted in the development of supplementary guidance for first line engineers attending to gas emergencies and meter works at the Keele University estate.

The supplementary guidance produced to support the implementation of the regulatory exemption means that operatives are required to conduct tasks in a way which differs from their regular (regulatory based) job training (known as EM72). As such Cadent and Keele University have worked together to develop training materials which are designed to equip operatives with the necessary supplementary information. This information enables those having completed the course to discharge duties safely in the HyDeploy environment (Keele University). The supplementary information has been compiled into a document called 'EM72Hhdrogen' (EM72H) which forms the basis for a one day training course, with completion of this course being a requirement for all operatives being made available [via the cadent job scheduling system] to attend gas emergencies and meter works. The one day training course certificate (also know as a ticket) is valid for 12 months post completion.

For the purposes of the SAV control process, the HyDeploy project is technically classified as a sub site of the estate, with the subsite being accessible only to Cadent employees who have met the HyDeploy Cadent Operative Specific SAV Control Criteria in addition to the General Estate SAV Control Criteria.

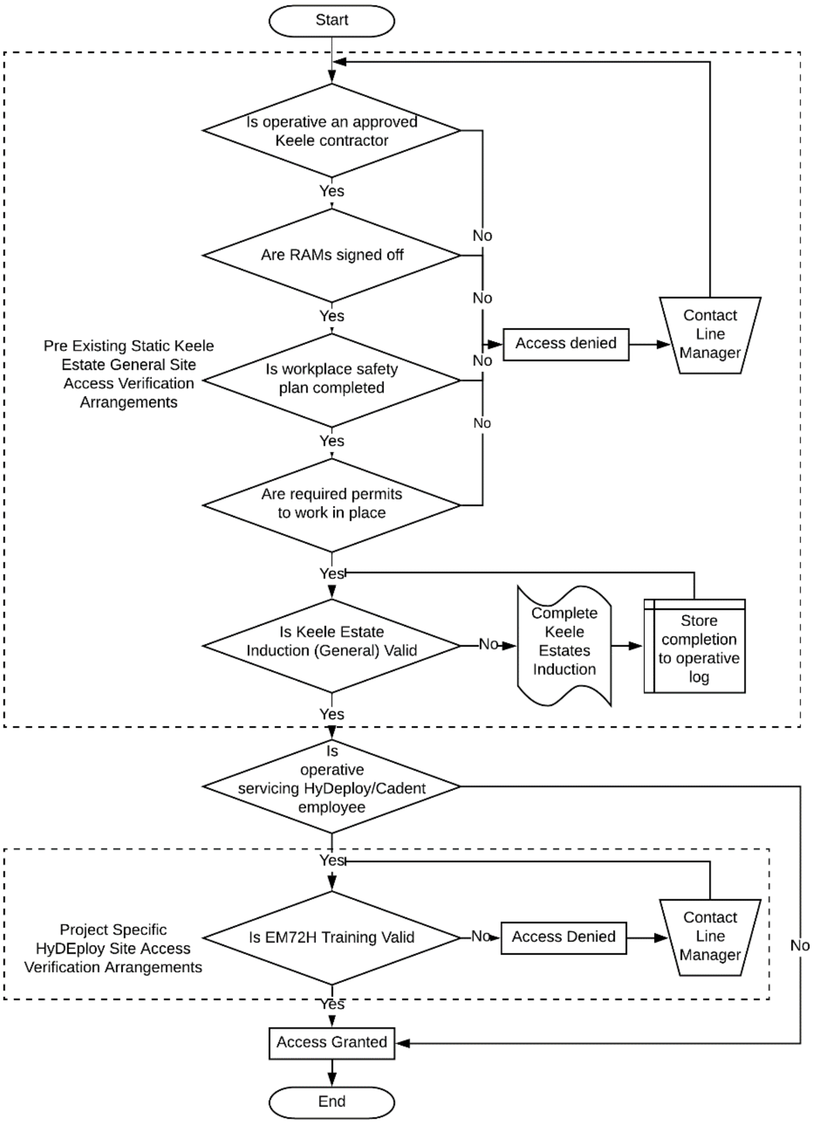


Fig. 1. Existing HyDeploy Cadent operative specific SAV control criteria

## 6 Results Analysis

Having reviewed and agreed the Existing HyDeploy Cadent Operative Specific SAV Control Criteria both research participants completed the initial questionnaire. The open ended nature of the questionnaires required a qualitative content approach to analyse the results. A number of key themes were able to be identified from the analysis of the results.

Change management was identified as the key theme with emerging smart technologies roll outs such as HyDeploy. Both participants reported that change management in respect of safety procedures (and associated health and safety training) requires very careful planning to ensure that compliance with the regulatory exemptions is maintained, and critically that the specifics of the exemption are understood by all operatives.

Both participants identified that the existing methods of SAV control do ensure that only trained operatives are authorised to attend site when emergencies are reported. Equally though both acknowledged that there are opportunities to further leverage technology to improve the solution. Most notably both participants identified operational challenges (specifically cost) regarding refresher training (post ticket expiry) as being key concern with one participant commenting, “renewal of authorisation cards and any ongoing changes that require an update or change of procedure within EM72H need to be disseminated and verified and at the moment the only process to complete this is by [face to face] training sessions/toolbox talks and Keele site visits. An alternative cost effective solution to change management and authorisation would be beneficial.” Indeed “Due to the widespread layout of gas operatives it would be unpractical and expensive to get all the operatives to site.” The compliance threshold for change management such as that required for this project requires very specific SAV control arrangements to be put in place, evidently there are cost implications arising from the operational challenges pertaining to the implementation of such control arrangements.

The second stage of the research was designed to determine research participant apparent acceptance of a solution to improve the current SAV arrangements (Figure 2). The solution being researched presents both the Estate owner/operator (Keele Uniersity) and the Contractor company (Cadent) the opportunity to improve the quality, accessibility and availability relevant information in a way which supports the communication of information which is of specific relevance to the project.

The SAV process can be developed to include new additional micro credentials which are able to cover a variety of topics. One such example of an additional credential can be seen in the form of ‘procedural amendment content’. In the case of a procedural amendment, under the existing arrangements an email would typically be sent out to the operative group, with all amendments being highlighted. The proposed arrangements supported by the solution being researched would enable content to be pushed to the user group (in this case all 100 operatives), providing the operative with a notification to the effect that new content is now required to be completed prior to the next operative visit to Keel University.

Note scheduling of content completion can be set according to the specific objectives of the content roll out, example immediate completion required. Prior to arrival at site the operative would access the content typically presented in the form of a short video, with completion recorded back to the system to support the SAV verification process and to support administration and auditing processes on both the estate owner/operator and client contractor side. Additional content can be pushed out by the solution, with short assessments set as content completion criteria where deemed relevant.

Figure 2 (Proposed Site Access Verification (SAV) Control Criteria Flow is representative of the content types which can be pushed out and the objectives which are able to be met by completion of such content. Additional content types covered by the solution include, reactive safety content which may have been generated according to the outcome of an accident investigation or near miss. The flow diagram was shared with the research participants for review prior to the sharing and subsequent completion of the final stage questionnaire.

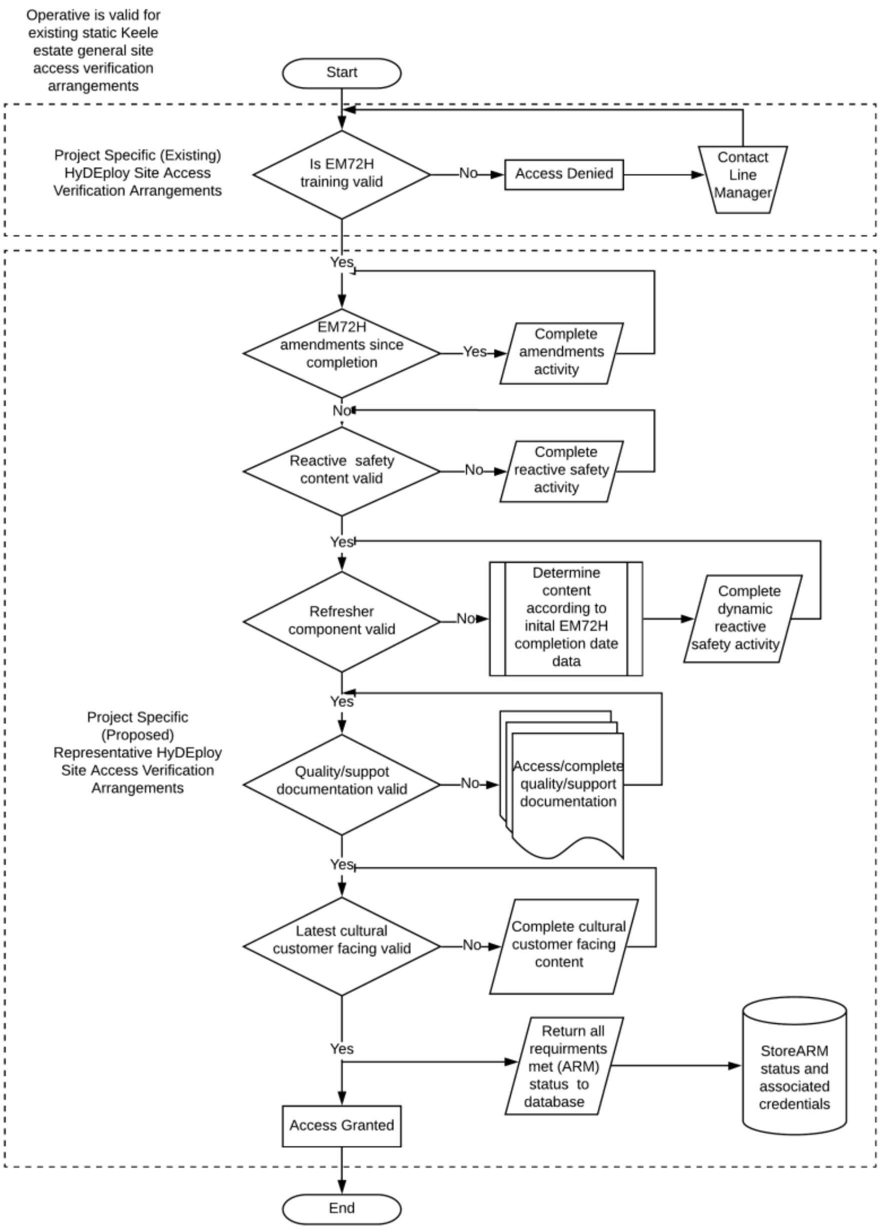


Fig. 2. Proposed Site Access Verification (SAV) Control Criteria Flow

Both participants agreed that the proposed solution would improve the level of confidence in the compliance position regarding HyDeploy SAV arrangements, with one research participant noting that the proposed arrangements would "enable a management team to have confidence that knowledge is transferred in a timely manner" and that data made available via knowledge check reporting would enable management teams to "determine the effectiveness of the training medium". A key theme emerging from the analysis of data from this stage was the perceived ability of the proposed solution to efficiently support the communication of minor alterations to existing procedures which is especially useful in pathfinder projects such as this one where "[site] specific hazards" exist.

When asked about potential challenges that may affect the implementation of such a solution, staff engagement and the need to ensure staff do not experience a feeling of "alienation" from the face to face training process was highlighted as a concern. Additional concerns raised related to, adequate process documentation and maintenance, the provision of available hardware, and the fact that e-learning can be a "frustrating" experience.

Regarding potential additional benefits of the proposed solution one research participant identified the opportunity to create communities around projects where specific risks exist, thereby leveraging the technology to ensure that opportunities which exist in classroom situations to "promote open conversations" are not missed and continue to inform training outcomes and development.

## 7 Conclusions

The HyDeploy project is demonstrative of the type of risk scenarios which may reasonably be expected to exist as the range of smart technologies solutions grows as part of a global response to the challenges associated with a growing population, increasing urbanisation and global warming. To address the increasing risk profile associated with this transition, specific responses are required to ensure that operatives are familiar with the change process and are protected from the increased risk profile.

This research demonstrated the specific SAV arrangements developed in collaboration with the UK HSL and implemented at the Keele University site. The research found that while the existing arrangements were required to be implemented to account for regulatory exemptions and ensure that associated changes to existing procedures and protocols relating to the presence of hydrogen (blended with natural gas) are communicated to a contractor group of 100 persons. The arrangements ensure that only trained authorised engineers attend the estate when emergencies are reported.

Expert input found that the current arrangements face change management challenges and are not cost effective especially in situations where amendments to completed training are needed. The research proposed a technology-enabled SAV solution as a way for improving the training outcomes for operatives and strengthening the confidence in the compliance position of contractors. Experts perceived the solution as having clear potential to improve the perceived compliance position of both the estate owner and the contract provider, asserting that operatives would be more well informed of change process relating to project specific risks under the proposed arrangements.

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# OPTIMIZATION OF A USER-INVOLVED FLOOR LAYOUT RECOMMENDATION SYSTEM AT THE OPERATION STAGE

**Junhan Wen[1], Elie Daher[2], and Sylvain Kubicki[3]**

**Abstract:** The parametric modelling method, an algorithmic thinking process based on visual programming, is recently established as a supportive tool in the decision-making practice for architecture. For the time being, the method helps to inform, control and optimize the architectural design by expressing the input parameters and conditional rules that are generated according to the design objectives. This paper describes how a parametric-model-based recommendation system is developed for an interior floor layout optimization problem which supports user involvement in different aspects of the process. The system connects the design objectives and the user preferences to propose customized space layouts in the operation stage of buildings, and one of the feasible relaxations of this design study is to substantially generalize it as a multi-objective optimization problem. As such, the algorithm- part of the system contains three different functionalities: (a) a screening scheme to select the available spaces concerning given requirements, (b) a generation process to figure out different possibilities of interior plans, and followed by (c) an evaluation system to compare and recommend the best-matching solutions. Simultaneously, the user interface of the system builds up various interactions between the users and the parametric models throughout the process of design, so as to collect the criteria, preferences, and priorities of the design objectives. The recommendation system is also implemented in a real case study, the floor planning of the IAK-1 building of the European Investment Bank in Kirchberg, Luxembourg, to assess the algorithm performance and user experience. The results illustrate the applicability of this approach in real-life design, and the pros and cons of the generated plans are also analysed by comparing to traditional designs given by expert architects.

**Keywords:** Floor Planning, Multi-Objective Optimization, Parametric Modelling, Algorithmic Design.

## 1 INTRODUCTION

The design of a complex interior space-planning layout is always a complicated task for design teams and facility management teams. One of the major challenges is to propose solutions that satisfy the client requirements, respecting the building standards and the needed characteristics. In practice with the traditional design method, finding a solution that answers most of the constraints and input is a complicated task under various limitations. Nowadays, with the capabilities offered by new technologies for architectural

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design process, there come possibilities to develop algorithms and programs to answer the design problems (Shea, Aish and Gourtovaia, 2005; Brown and Katz, 2011; Krish, 2011; Stavrić and Marina, 2011; Lee, Gu and Williams, 2014). Among the previous researches, one of the major limitations with the analytical optimization techniques is that the end users cannot always involve in the main design process.

Recently, the application of these computational methods has increasingly been thriving for interior space planning. Many researchers and practitioner architects are trying to investigate in generating space planning with the support of computational tools. The focus of this research is to enable the participation of users in the re-allocation of the interior floor plan with new functions, with employing programming-based systems: a series of algorithmic and parametric design tools combined with other participative devices such as tangible tabletops and graphical interfaces. Design decisions are recommended by an algorithm developed for this purpose with the help of parametric building data. Besides, the users are also given the ability to evaluate the design from the visual performance indicators running on the graphical and participative interfaces.

## 2 Related Work

### 2.1 Space Planning and Generative Algorithm

Several academic and applied pieces of research were developed to investigate the generation and optimization of space planning with the use of computational architectural tools (Dutta and Sarthak, 2011). Boon et al. (2015) created an analytical system intended to enhance efficiency within the groups of the complexly-interconnected architectural program considering the adjacency between the spaces (Boon *et al.*, 2015). Another attempt developed by the architectural office Shepley Bulfinch aimed to determine the overall form and function of a building connected to a BIM tool, in order to provide a platform for programming and generating early geometrical form with physical and numerical parameters as input, i.e. size, shape, purpose and adjacency between functions (Nagy *et al.*, 2017). The Autodesk researchers also worked in developing a flexible generative workflow that creates a variety of space planning layouts including locating all necessary programs and people using a limited set of input parameters in two of their researches (Nagy *et al.*, 2017; Villaggi *et al.*, 2018). Bahrehmand (2017) developed a genetic algorithm for space planning with a multi-parental recombination method (Bahrehmand *et al.*, 2017). In another research, Das (2016) created scalable algorithms from computational geometry to deliver rational architectural space plans (Das, 2017).

In general, the proposed studies well implemented the generative algorithm into space planning, among which some systems were also able to generate satisfactory-feasible floor plans based on spatial quality metrics. Nevertheless, when the decision is generated based on the designer's taste, limitations occur when the specific requirements from the end-users and the corresponding participatory approaches during the design progress need to be concerned. Since the design objectives and specifications change very often from the users, a system that integrates the first party in the process is necessary to be developed.

## 2.2 Decision-Making in Multi-Objective Question

In this specific case, since the separations and circulars are fixed at the operation stage of the interior layout, the problem of optimizing the office floor plan, could be essentially interpreted as a multi-objective allocation problem, of which the solutions might have the fitness from diverse aspects. For this master problem, two main directions of finding solutions are suggested, either classifying solutions from a best non-dominated level, or projecting the solutions to a created dimension so as to have a comparable objective function. Aligning to the former suggestion, Chaharsooghi et al. enhanced the ant colony optimization algorithm to figure out an allocation (Chaharsooghi, 2008), and Govil considered the cost of re-allocation as the objective to be optimized (Govil, 2011). Since the design problem in the operation stage limits the number of plan possibilities, it makes the constraints more stringent than common NP-hard problems. Therefore, it would be better to consider the problem as NP-complete in this specific situation, from which a searching scheme could be figured out to find the global optima with minimum iterations. Simultaneously, the use of a mathematical tree to reduce the search space for this type of problem (Garey, Graham and Johnson, 1976; Pan, Yu and Wang, 2003; Sun, 2004), inspires a direction to enhance the computing efficiency of defining the scope of searching.

In terms of deciding the objective function, fuzzy logic is taken into consideration because it is commonly employed as a control rule to decide the degree of output membership [16]. As illustrated in Figure 1: Illustration of the Fuzzy Logic.Figure 1, at least two control values are required to represent the critical range of 1 and 0, and the output will be calculated linearly when the input is between the thresholds. This rule is implemented in many optimization algorithms. For instance, Kumar et al. defined rules to decide the temperature-control parameters for a process (Kumar Singh, Singh and Gangwar, 2018). Chaouali et al. and Leonori et al. used fuzzy logic to supervise the energy management strategy (Leonori, De Santis, Rizzi and F. M. Frattale Mascioli, 2016; Leonori, De Santis, Rizzi and F. M.Frattale Mascioli, 2016; Chaouali *et al.*, 2018). These researches validate that fuzzy logic is a practical parameter configuration method as it could form a mono-objective function through convex combinations effortlessly.

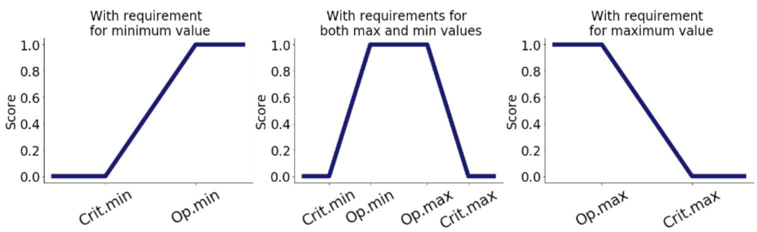


Figure 1: Illustration of the Fuzzy Logic.

Previous parametric modelling studies show that the time needed for computing and optimization is one of the substantial constraints and challenges of parametric modelling design in practice (Bittermann, Ciftcioglu and Sariyildiz, 2009; Dino, 2012; Zarei, 2012). Responding to this, fuzzy logic could be a choice to save the computing power, owing to its linear way of degree evaluation. Meanwhile, for this specific multi-objective optimization problem, some simulation results might give contradictory recommendations. Hence, instead of finding a feasible non-dominated dimension, the concept of creating combinations to form a new objective function could play as a better role, i.e. considering projecting to a self-defined dimension. In this case, the linear way of combination from fuzzy logic could also help in limiting the running time of functioning. Hence, fuzzy logic is decided as the major tool to evaluate the plan performances.

# 3 Problem Description

## 3.1 Research Gap

Traditionally, space planning layout is designed by the architects, and the influences of noise, light, thermal comfort are considered empirically from a qualitative perspective. Nevertheless, the development of building simulation technologies gives more information and opportunities for the design process and design solutions. These solutions are generated in a top-down optimization approach, and the involvement of users is limited in the initial phase of the design process. This brings out a question: how to make appropriate deployment of the simulation data to optimize the working environment layout, which both meets the design constraints and allows a high level of users involvements throughout the process?

Concerning the research status of parametric design, a study is incubated to bridge the involvement of architects and users during the design phase. To answer the gap, a solution is proposed to create parametric interactions between the end-users and the allocation of functions of rooms in the layout of the office spaces. From a human-oriented aspect, it provokes another research question: how to facilitate this computational procedure to customize the plan in order to achieve an interactive and favourable user experience?

## 3.2 Research Objectives

Essentially, the study aims at developing a system that is capable to find the space planning layout of a building that fits the characteristics of the new functions so as to best re-allocate the floor plan according to the customer's definition of specific needs. The core algorithm aims at achieving the best coupling between the inputs of requirement and preferences from customers and the physical comfort of the building. Specifically, the objectives of this study are:

- To develop a scheme to quantify the space characteristics and user preferences.
- To form and optimize a planning algorithm in order to figure out the optimal solution from the two inputs in a qualitative and fast-functioning way.
- To visualize the result in clearly and concretely so that the users are able to compare and select their favoured plan(s).

# 4 Methodology

## 4.1 Assumptions

Some assumptions and constraints are made before developing the system:

- **Concerning the main task:** The system works on optimizing the floor plan at the operation stage, with all the separation walls and circulars constructed. Therefore, the new plan will be generated by re-allocating the newly-required functions of rooms (hereafter, called "functions" for short) into the existing interior spaces (hereafter, called "spaces" for short). Nevertheless, in case a larger area for a specific function is asked, there should be suggestions for removing the non-structural walls to form a larger space.

- **Concerning the space feature input:** The features of spaces consist of individual characteristics of each space, and the adjacency level between every two spaces. The individual features include the noises level from interior and exterior, the daylight and the radiation received during a year, as well as the views to the outside and to avoidable places like the restrooms. Due to the limitations of the model, such as available weather data and simplification during the simulation process, the space features cannot always present the absolute conditions. Nevertheless, since the algorithm considers the "best-fitting solution", which principally expects the comparative space conditions to be illustrated, the values of these features are still practical for the recommendation system.
- The connection between spaces, recorded in a symmetric matrix4, are classified into three levels: (a) the highest level for horizontally adjacent spaces, (b) the medium level for spaces that could be reached vertically (close to a staircase or an elevator), and (c) the lowest for the rest cases.
- **Concerning the user-involving input:** On the starting stage, the customers are asked to define the priority class of every function. Then the requirements of each function could be given either quantitatively or qualitatively. The qualitative inputs, such as "the best 10%", will be quantified by an auxiliary module5. The favoured levels of features given by the customer are considered as the optimal range, and the system will also generate a larger value range, called the acceptable range, based on the priority classes. In addition, the customer is asked to provide the desired adjacency levels between specific room functions.
- **Concerning the scoring of fulfilment:** According to the application of fuzzy logic in decision making, when the space feature fulfils the optimal range, the score of the sufficiency will be 1. When the feature lies outside of the optima but within the acceptable scope, the score will be calculated linearly. When it is not in the acceptable range, the sufficiency will be 0 and the allocation of that function-space will be considered as invalid, i.e. the acceptable range also defines the critical values of the function requirements. These thresholds could also be altered manually if requested by the customers or building standards. Since the space adjacency is a descriptive feature, the evaluation will use a scoring dictionary instead of the fuzzy logic, ranging from 0 to 1, and no more acceptable ranges will be established for this requirement.

## 4.2 Conceptual Framework

The conceptual framework proposed is grounded in a wider theoretical paradigm developed and related to a Ph.D. study addressing the participation of users in the design as a new societal challenge essential to answer (Daher, Kubicki and Pak, 2018).

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[4] The adjacency matrix uses names of functions as both the columns and rows, while each element shows the level of connection requirement of the two elements of its position. Hence, the result matrix will be symmetric, i.e. $A = A^T$.

[5] The auxiliary module means another python program that will run when the expert requires. The input will be the rank, shown as a number or a percent (e.g. best 5 spaces or best 10%), and the output will be the suggested value of feature requirement that could give to the system.

As illustrated in Figure 2**Erro! Fonte de referência não encontrada.**, the plan-optimization system starts with calculating the decision thresholds, and then screens the eligible spaces for each function. When there is no space that could meet all the requirements for certain functions, the system will suggest various possible approaches to deal with this circumstance. The bottom line of the optimization-computing procedure consists of three sections: plan generation, evaluation and recommendation. In the plan generation part, the system will allocate the functions to the interior spaces with respect to the specific screening results. The generated plans will then be ranked by scoring, which evaluates the overall sufficiency with weights on different features. After the assessment, the best *n* plans (using *n*=10 as a default value) will be recommended, and the final decision will be discussed with the customers, in case some cognitive perspectives are concerned. Parametric models of the saved plans will be fast rendered in Rhino, which could visualize the optimized layouts as 3D models to convene the decision of the customers.

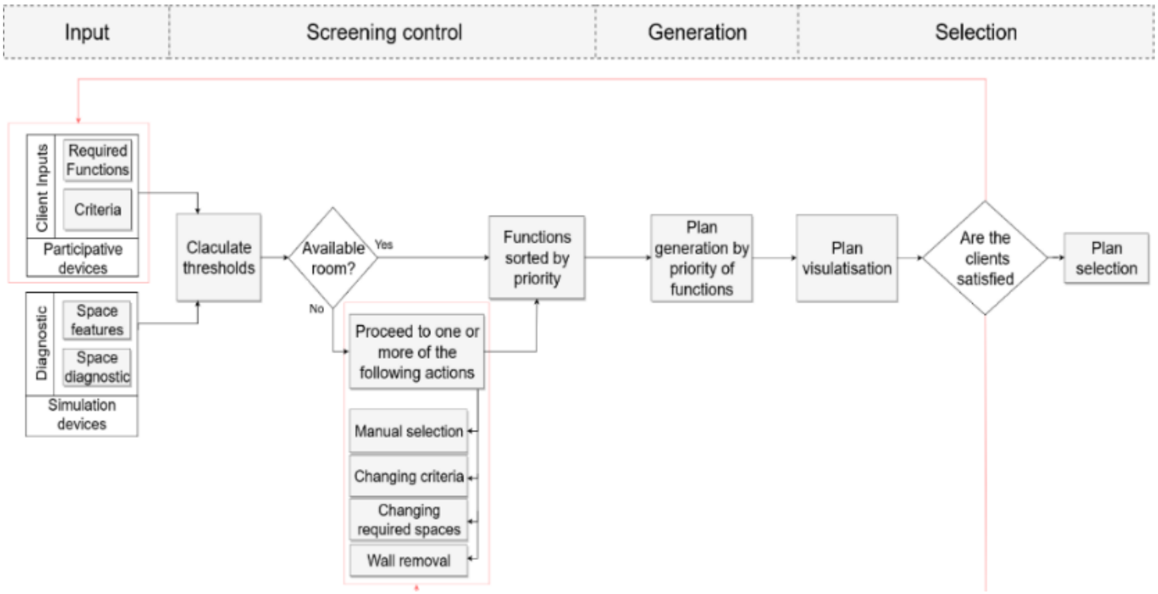


Figure 2: Illustration of Design Workflow.

## 4.3 Technical Framework

The algorithm is practised as a real-case prototype. The computation environment comprises Rhino[6] for the 3D modelling of the building structure, Grasshopper[7], the plugin for Rhino for building simulation and visualization, and Python[8] for the core algorithm development. In addition, a tangible tabletop is used as an auxiliary tool for user interface during the process and for connection with the database by PostgreSQL[9], which is also synchronized with the Python program.

6 Rhino is a 3D modeler used to create, edit, analyse, document, render, animate, and translate Non-Uniform Rational B-Spline (NURBS) curves, surfaces, and solids, point clouds, and polygon meshes. The paper uses the latest version of Rhino 6.

7 Grasshopper™ is a graphical algorithm editor tightly integrated with Rhino's modelling tools.

8 Python is an open source programming language. The core algorithm uses Python 3.6, together with the packages NumPy, Pandas, Math, and Psycopg2 etc.

9 PostgreSQL is an open source object-relational database system that uses and extends the SQL language. With Psycopg2, the program could take the input directly from the database.

### 4.4 Algorithm Development

Since the program covers different manipulations of information from multi-platforms, the development starts with a demo system with a small bunch of data, aiming at associating the data flow of the entire process. Then the algorithm is improved repetitively based on its performance shortcomings. This trial-and-error procedure is established as an iterative design approach to promote the final design to be reliable and practical.

## 5 ALGORITHM OPTIMIZATION

The workflow of the first demo system is to generate all the function-space allocations as the first step, and then to screen the allocations to ensure the allocated spaces meet the critical requirement of the corresponding functions. After that, the best-fitting plans are recommended. In short, it is called a G-S-O process (Generation-Selection-Optimization).

In the optimization part, the sufficiency of pairs of functions and spaces are calculated by fuzzy logic, which linearly calculates how much percent the space feature fits the optimal scope of the corresponding function. For assessing the descriptive adjacency requirements, the system uses "Boolean comparison", i.e. "*true (=1)*" for having an equal or better connection as required, and "*false (=0)*" for not holding.

The major problem arises from the first test is that a considerable long time should be spent if all the permutations are generated. With the increasing number of spaces and functions, these allocations will holding a complexity of $O(n!)$, i.e. grow in a factorial way. For instance, when allocating 5 functions into 10 spaces, the possibilities will reach a number of $A_{10}^{5} \approx 3 \times 10^{4}$. Whilst allocating 10 functions into 20 spaces, the possibilities grow to $A_{20}^{10} \approx 6 \times 10^{11}$, and require over 20 GB for storing afterwards.

To reduce the computation time, two methods are considered to improve the performance. First of all, the "priority" is added as a feature to classify the functions. Instead of finishing the entire process in one turn, the system iterates the G-S-O procedures within every priority class. For the previous example, those $6 \times 10^{11}$ plans could be reduced to $2 \times 3 \times 10^{4} = 6 \times 10^{4}$ plans. In addition, the customer could also interact with the system and select plans for the next iteration at the end of each loop.

The major problem that is causing the large computation power is that all of the functions have the chance to be placed into every space. Nevertheless, due to various requirement of every function, a large percentage of the plans could not have all the function-space allocations fulfil the critical needs. Essentially, the stricter the requirements are, the larger the combination storage wastes. Thus, another improvement is to utilize the selection result in the generation procedure, i.e. the algorithm considers the screening control before starting the design permutations.

With iterative research and experiments, a new combination algorithm is figured out as generating the function-space allocations as a tree structure. It starts with deciding the sequence of planning according to the number of possibilities. In the first step, the function with the least available spaces are allocated, and each pair of function-space forms one parent node. Then, the function with the second least available spaces forms the children leaves of that node, with removing the spaces "occupied" in the corresponding parent node. In the end, every branch in this tree forms an eligible allocation possibility without duplication.

An example of the plan generation method is shown below. Assume that 3 functions (F1, F2, F3) need to be allocated into 6 spaces (S1, S2, ..., S6), where F1 could be allocated into S1, S2 and S3, F2 has only S1 eligible, and F3 could be put in S1, S2, S3 and S4. For the enumeration method, a large proportion of allocations will not be available, including all of the plans which consider S5 or S6. As the new method illustrated in Figure 3, the only 4 capable plans are generated efficiently as the leaves of a tree.

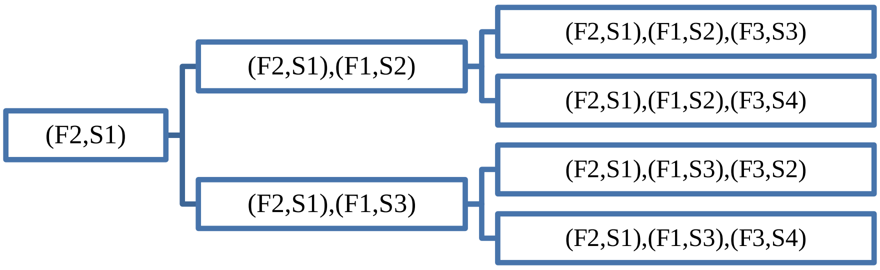


Figure 3: Example of the Tree Combination Method.

Meanwhile, there could also be the circumstance when not all of the branches consist of exactly the same functions. In this situation, the system will firstly select the longest branches of the tree, i.e. comprising the most of functions. When the branches have the same lengths yet their contents of functions do not, the system will construct additional data frames for the additional selections of functions so as to make reasonable comparisons among plans.

Some small improvements are also made in the optimization process. For the scoring of individual features, fuzzy logic is seen as an efficient and practical solution. For the evaluation of adjacencies, a renewed score dictionary is developed to make situation-wise punishments, as shown in Table 1. The full score of the adjacency is scaled to be equal to that of other features in the branch.

Table 1: Scoring Dictionary of Adjacency.

| **Request** \ **Obtain** | 0 | 1 | 2 |
|---|---|---|---|
| 0 | - | - | - |
| 1 | 0 | 1 | 0.7 |
| 2 | 0 | 0.3 | 1 |

At the end of the algorithm, the weighted sum of the sufficiency scores will be the decider for ranking and for choosing the optimal solution. Thereafter, to limit the number of branches, only the best 10 plans will be selected as the recommendations in that priority. Before going to the next iteration, the customers could check the visualized plan and modify or select some plans to better meet their underlying principles.

# 6 CASE STUDY

## 6.1 Implementation

The system was tested in IAK building at the European Investment Bank, situated in the Kirchberg quartier in Luxembourg, and as depicted in Figure 4. The case study was to allocate 12 functions of rooms to a target area that includes 19 spaces distributed in the first two floors, which are 8-meter and 4-meter-high respectively.

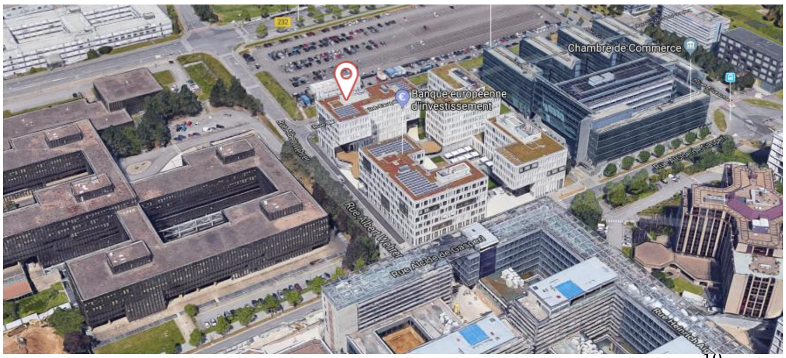


Figure 4: The neighbourhood of the IAK-1 Building[10].

The case study starts with modelling the building structure and its neighbourhood, from which the comfort simulation can be done. As previously mentioned, these simulation results compose individual space features. Selected results are depicted in Figure 5.

[10] Source: https://www.google.ch/maps/@49.6206851,6.1472378,230a,35y,357.89h,56.1t/data=!3m1!1e3

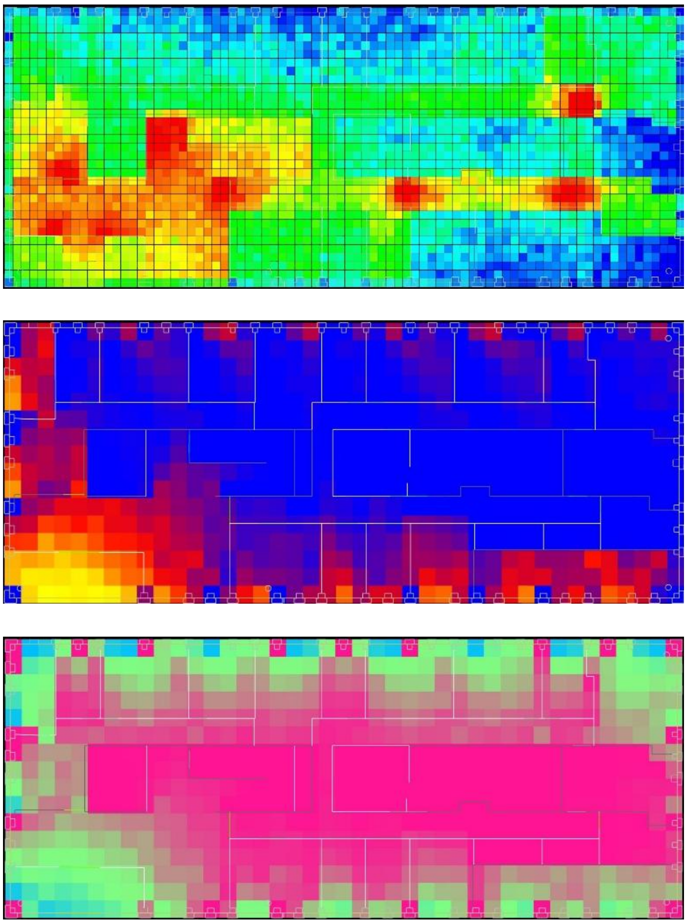

Figure 5: Simulation Results of the Internal Noise Level (top), Daylight Hours (middle), and Skyview from Windows (bottom) of the first floor from Grasshopper.

In the study, the functions are divided into 4 functions in Priority A and 8 in Priority B. With the latest plan generation method, the number of possible plans for the A priority is reduced from $A_{19}^{4} \approx 9 \times 10^{4}$ to 60. Then 10 best plans/nodes of the A-priority are retained, from which the branches of the B-priority start to grow. At the end of the Priority B, 404 plans with different numbers of functions are generated. According to the algorithm, only the longest branches are kept. Hence, 20 best plans with two combinations of 10 selected functions are kept as the recommendation, whereas 2 functions are not allocated. In this situation, the system will ask whether the customers want to consider the wall removal suggestions or to manually give their arrangement, referring to the sufficiency score of the specific function-space allocation. All of the decisions will be made with the help of a tangible table and a series of graphical interfaces. In Figure 6, three visualizations of the plan recommendations after Priority B are illustrated.

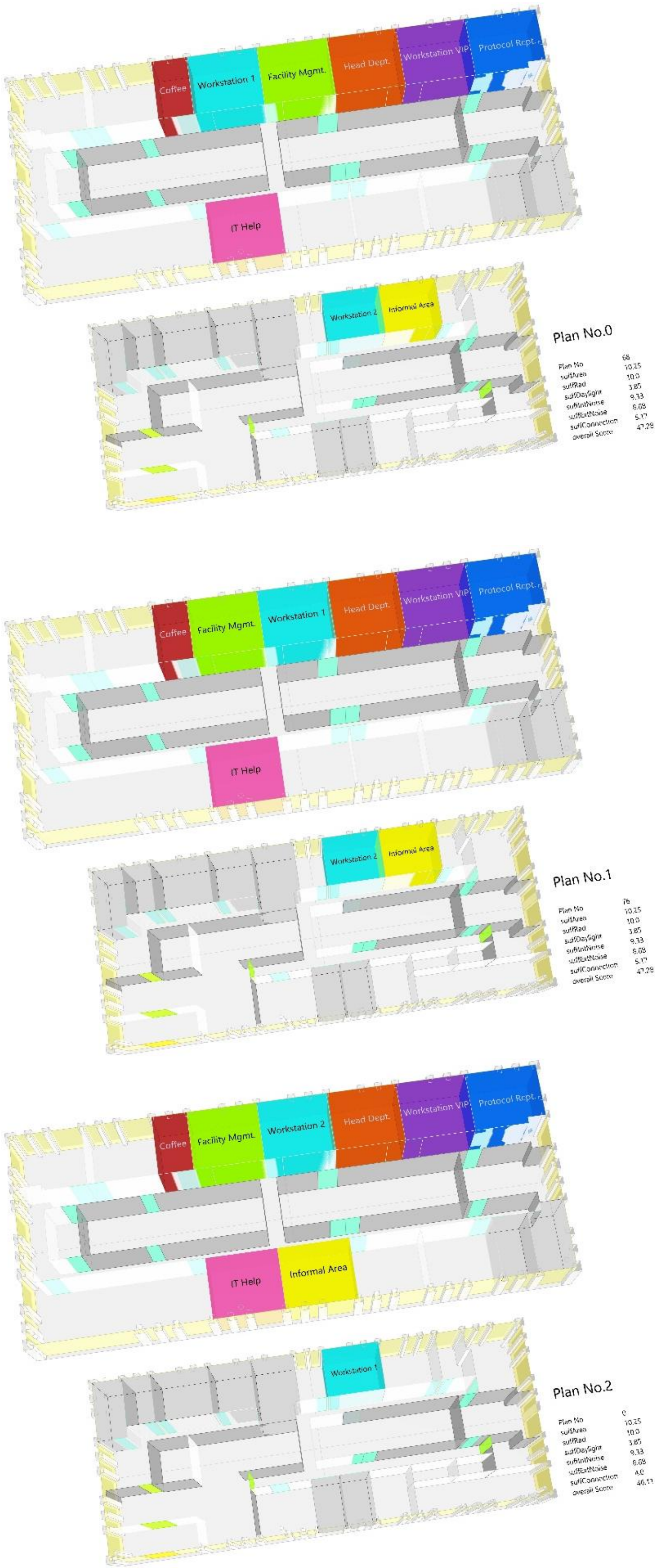


Figure 6: Visualization of the Top Three Plans Recommended by the Algorithm.

## 6.2 Results

Table 2 presents the scores of five recommended plans after the final iteration of the optimization system. The final score is the weighted summation from the six sufficiency scores. For simplification, the score in Table 2 is evenly weighted. The average score is the sum score divided by the number of comprising functions.

As is depicted, the two best plans have the same degree of sufficiency according to the proposed requirements. Since in total 10 functions are allocated in the recommendations, the results indicate that the selected plans have excellent sufficiency in terms of area and radiation requirements and good performance of environmental noise. The scores of direct daylighting imply a relatively lower performance compared to other criteria, which might due to the insufficient lighting condition of the whole building, as could be referred to in the middle of Figure 5. Since the degree of connection is a group feature of specific combinations, it might be limited by the plans that are generated by only screening the individual space features. Thus, the adjacency score is not horizontally comparable with other features. Nevertheless, this criterion is, to some extent, the decider of the final recommendations under this specific circumstance.

Table 2. Sufficiency Table of Generated Plans Sorted by Overall Score

| Plan No. | Use of Functions | Suff-Area | Suff-Rad | Suff-Daylight | Suff-IntNoise | Suff-ExtNoise | Suff-Adjacency | Sum Score | Avg Score |
|---|---|---|---|---|---|---|---|---|---|
| 68 | 10 | 10.25 | 10 | 3.85 | 9.33 | 8.68 | 5.17 | 47.28 | 4.73 |
| 76 | 10 | 10.25 | 10 | 3.85 | 9.33 | 8.68 | 5.17 | 47.28 | 4.73 |
| 0 | 10 | 10.25 | 10 | 3.85 | 9.33 | 8.68 | 4 | 46.11 | 4.61 |
| 92 | 10 | 10.25 | 10 | 3.85 | 9.33 | 8.68 | 4 | 46.11 | 4.61 |
| 60 | 10 | 10.25 | 10 | 3.85 | 9.33 | 8.68 | 4 | 46.11 | 4.61 |

## 6.3 Design Evaluation

The recommendations from the algorithm are also compared with the plans designed by experienced architects under the same qualitative constraints[11]. Three senior architects and one building engineer were involved in this experiment. The evaluation and screening results are summarized in Table 3 and Table 4 respectively.

The assessment of "overall available allocations" is calculated by accumulating the combinations of functions-spaces that meet all of the critical requirement of the six criteria of individual features. Compared to other single criteria, the rather low values in the overall availability demonstrate that one of the most challenging objectives for human experts when figuring out the solutions is to ensure the decision performance meets the thresholds from every perspective simultaneously. Since the fuzzy logic does not give negative scores even when the object value is far out of acceptable range, it is indicated that there might be potential accomplishments in the traditional design to be overestimated. On the other way, it is demonstrated that one of the major competencies of the algorithm is to ensure the operation performances of the generated plans are all within the constraints of critical requirements.

[11] All the constraints considered simulation results are given qualitatively, e.g. "the best daylight" or "medium noise level". The optimal areas of functions are given the same as to the program.

Table 3. Sufficiency Table of Architect-Designed Plans.

| Plan No. | Use of Functions | Suff-Area | Suff-Rad | Suff-Daylight | Suff-IntNoise | Suff-ExtNoise | Suff-Adjacency | Sum Score | Avg Score |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 10.97 | 9 | 8.09 | 11.33 | 8.56 | 3.15 | 51.10 | 4.26 |
| 2 | 12 | 11.87 | 10 | 7.71 | 10.33 | 10.88 | 6.15 | 56.94 | 4.74 |
| 3 | 11 | 10.92 | 7 | 8.38 | 9.66 | 9.88 | 5.64 | 51.48 | 4.68 |
| 4 | 12 | 9.35 | 11 | 9.17 | 11 | 9.41 | 2.55 | 52.48 | 4.37 |

Table 4. Eligible Function-Space Allocations from Architect-Designed Plans.

| Plan No. | Use of Functions | Avail-Area | Avail-Rad | Avail-Daylight | Avail-IntNoise | Avail-ExtNoise | Overall Available Allocations | Time [min] |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 11 | 9 | 10 | 12 | 10 | 5 | 30 |
| 2 | 12 | 12 | 10 | 9 | 12 | 11 | 6 | 20 |
| 3 | 11 | 11 | 7 | 9 | 11 | 10 | 5 | 25 |
| 4 | 12 | 10 | 11 | 11 | 12 | 10 | 7 | 30 |

# 7 DISCUSSION

## 7.1 Conclusion

The study demonstrates how parametric data could be used in floor plan generation and optimization, plus how customer interaction could be integrated into this design process.

The plan generation algorithm considers the possibility of allocating diverse functions of rooms into separated spaces in the interior floor layout. In order to increase the efficiency in practice, the algorithm generates a mathematical tree store all the eligible plans, and uses pre-defined priority categories to limit the computation power in each run. The optimization procedure recommends the plans that best suffice the optimal user requirements comprehensively, of which the assessment is made based on fuzzy logic for quantitative features and situation-wise scoring dictionaries for descriptive items.

During the entire procedure, the customers have several opportunities to interact with the design. The most important information is the optimal value ranges for each criterion and the priority category of each function, which are given through a tangible tabletop connected with a database in the cloud. Besides, elective propositions from customers are also established in the interface for further requisites. For instance, the customer could check the suggestion of change the floor layout by moving non-structural walls, or they could have manual placement of particular functions. When making the final plan decision, they could also give their preferences for specific types of space criteria, by giving weights of the sufficiency scores to influence the final ranking. At the end of each iteration, the customers also have the opportunity to select the preferred plans directly, or apply some additional manipulation. Altogether, all of these interfaces ensure the algorithm to customize the plans as decisive as possible from the end user's request, which build up the core concept of the program.

When comparing the algorithm outcomes with the outcomes from experienced architects, it is shown that the plans from the architects would be able to locate more functions, yet some spaces' comfort condition is overestimated. Hence, the two advantages of the plan optimization algorithm could be indicated. For one thing, the algorithm shows better decisions while working on cognitive parameters by utilizing the simulation results. For another, the comprehensive plan generation scheme, which considers all the ranges of acceptance, could better guarantee the user experience in the long-term operation.

### 7.2 Future Study

Still, there are some limitations in the study. For instance, it is only implemented in the operating stage on the current stage, with all the separations and circulars pre-defined. Based on such constraints, the solution algorithm narrows down the sorts of cases that it could be further applied. Accordingly, it is suggested that some optimization methods for NP-hard problems might be further directions to broaden the scope of application. More importantly, more interactions in the early design phase could benefit more for the core idea of achieving high user involvement.

During the plan generation process, the algorithm emits re-simulation to save the reacting time. Nonetheless, the change of floor plans might alter the room characteristics such as noise sources, internal viewing, etc. Therefore, figuring out a reliable approximating process of update features could also help to improve the feasibility.

Last but not least, some accesses of user interactions are proposed in this algorithm, i.e. removing non-structural walls, manual allocation of function-space, and searching the spaces out of the original definition etc. These interactions have mock-ups of codes now but are not yet integrated into the program and the tangible user interface. Therefore, figuring out better suggestion methods and integration of the interactions should better support the achievement of the algorithm by enhancing user involvements in design.

## 8 Acknowledgement

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# FRAMEWORK PROPOSAL FOR A BIM-BASED DIGITAL PLATFORM FOR FLEXIBLE DESIGN AND OPTIMIZATION OF INDUSTRIAL BUILDINGS FOR INDUSTRY 4.0

**Julia Reisinger[1], Iva Kovacic[2], Hannes Kaufmann[3], Peter Kán[4], Iana Podkosova[5]**

**Abstract:** The production of the future, respectively industry 4.0, is a highly networked, digitized and thus individualized production, leading to shortened product lifecycles and constantly changing processes. Industrial buildings need to be capable to react to these varying conditions, making the realization of flexible building systems necessary. Inflexible building structures lead to early rescheduling or even demolishing, resulting in increased life cycle costs and material demand. The load-bearing structure is decisive for maximum flexibility as it is the most rigid element with the longest service life. The planning of flexible building structures and the consideration of production in building design requires maximum integration of all stakeholders in early design stage. However, early integration of all stakeholders, processes and tools is rare and difficult due to the lack of interoperability of domain-specific software and sequential planning methodology. This paper presents the ongoing research conducted within the research project BIMFlexi. The goal of BIMFlexi is to make industrial buildings efficiently adaptable to rapidly changing production processes by developing an integrated BIM-based digital platform to enable flexible structural analysis, taking into account changing production processes and support in multi-objective optimization and decision support. In this paper, potentials and limits for integrating processes and discipline specific models of building and production planning are identified and a framework for a "BIM-based digital Platform for Flexible Design and Optimization of Industrial Buildings for Industry 4.0" proposed. The proposed framework couples digital tools such as BIM, parametric modelling, structural analysis and VR within a platform to allow multi-objective optimization and early decision making in real-time.

**Keywords:** BIM-based digital platform, integrated planning, industrial building, multi-objective optimization, performance-based structural design.

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## 1 INTRODUCTION

The fourth industrial revolution is already established in many manufacturing industries (Woodhead et al., 2018) but the benefit in terms of improvements in productivity and quality, has not gained much attention in the construction industry (Oesterreich and Teuteberg, 2016). Short production cycles and constantly changing production systems are characterizing the production of the future. For industrial buildings, these rapid changing processes mean extremely short planning and construction times, as well as the necessity of implementing highly flexible building systems. In future, buildings, including structural and energy systems, must be able to react to these production changes, individual customer requirements and changes in use (Wiendahl et al., 2014, Bracht et al., 2018). Decisive for a building's adaptability are the structural and building service equipment (BSE) systems. The ability to convert and retrofit is most strongly influenced by the load-bearing structure, as the most rigid element with the longest service life. Structural engineers are usually involved too late in the traditional planning process, resulting in suboptimal floor plans and load-bearing structures, poor building quality and reduced utilization (Li, 2018). Mostly rescheduling or even demolishing and new construction are the result.

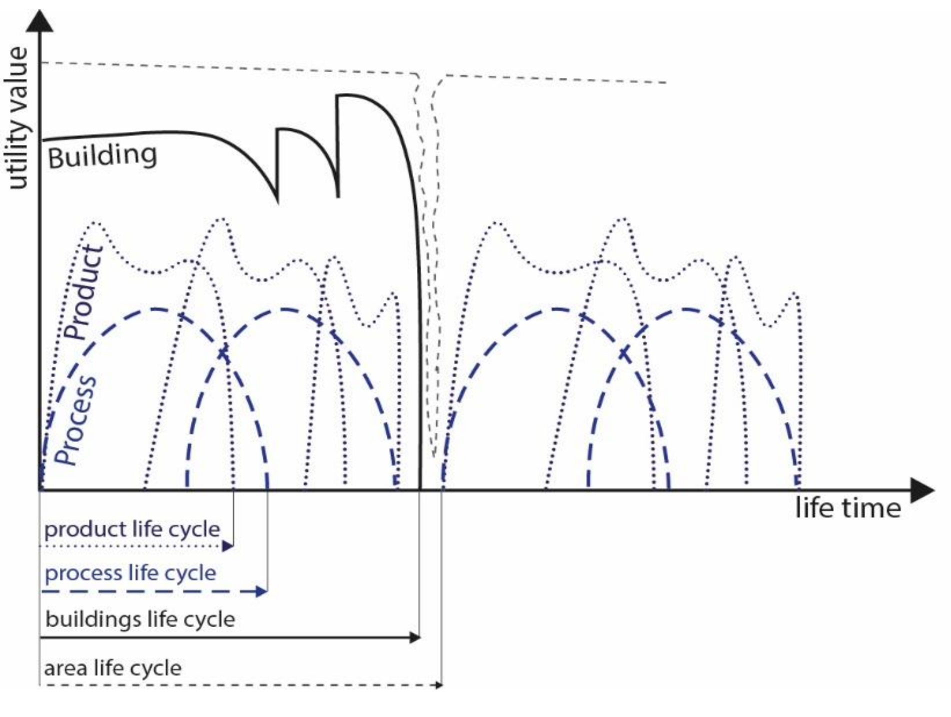


Figure 1: Life cycles of a factory -own presentation based on Wiendahl et al. (2007)

Wiendahl et al. (2007) highlight the importance of designing structures, which are able to meet the changing requirements of production businesses. Integrated planning in industrial construction requires a high degree of networking, coupling and coordination of processes and discipline specific-models for all involved stakeholders, leading to increased complexity. Although digitization and Building Information Modeling (BIM) deployment in the construction industry are advancing rapidly, most common digital tools' configuration is domain-specific for single disciplinary use (silo-use) and offer a low degree of interoperability. Especially in early design stage, which is crucial for the definition of essential parameters influencing the entire life cycle, the identification and integration of all stakeholders, processes and tools is rare and, in addition, technically fraught with obstacles due to the lack of interoperability of domain-specific software tools and process-related because of sequential planning methodology. Integrated industrial building models, which integrate production into building design and vice versa, are however, rare and data exchange and data continuity do not exist.

New digital technologies, such as BIM, algorithmic modelling, automation methods or Augmented and Virtual Reality (AR/VR), have the potential to support interdisciplinary industrial construction projects, but are not fully exploited yet. Flexibility and neutrality in use, an integrated planning methodology in early design stage, the interoperability of digital tools and methods for multidisciplinary optimization and decision support were identified as the most important requirements for planning and operation of flexible industrial buildings.

This paper presents the ongoing research, conducted within the research project BIMFlexi, funded by the Austrian Ministry for Transport, Innovation and Technology through the Austrian Research Promotion Agency FFG (Grant No.: 877159). The primary goal of BIMFlexi is to make industrial buildings efficiently adaptable to rapidly changing production processes by integrating production planning into building design. This paper investigates potentials of coupling digital planning methods (BIM, generative design and structural analysis) with multi-objective optimization methods and multi-user VR to support integrated industrial building design. Its main goal is the proposal of a novel framework for a " BIM-based digital Platform for Flexible Industrial Building Design 4.0", enabling the integration of production into building design, supporting design, analysis and optimization of flexible building structures by providing visualization and decision support in real-time.

## 2 LITERATURE REVIEW

### 2.1 Flexibility in Structural Design

The structural system strongly influences the transformability of a production system. The supporting structure must allow changes and be technologically upgradeable with a minimum of capital and technological investment. If the load-bearing structure is designed for flexibility, costs and time required for renovation can be reduced (Slaughter, 2001). The rigid supporting structure has a service life of approximately 50 to 100 years; in comparison, the BSE has a service life of 10 to 20 years (Fastabend, 2002). Flexible load-bearing structures, which can be implemented by means of wide-span ceiling or girder systems, sufficiently high storeys and different load carrying capacities, can prolong building's service life without expensive conversion measures (Graubner, 2014). Early variant studies taking into account possible scenarios of production layouts could support in designing flexible and re-configurable load bearing structures. However, early variant studies considering multi-criteria parameters are rarely carried out in structural design, as they are complex and require maximum stakeholder integration.

### 2.2 Integrated Planning Methodology in Industrial Building Design

AEC belongs to the least digitized industries, still caught in silo-thinking and sequential planning processes (Schober, 2016, Agarwal, 2016). As an emerging digital tool, BIM offers a common digital knowledge platform integrating the activities of all stakeholders along the construction value chain (Succar, 2009, Zhang et al., 2018). BIM aims at the integration of different data models - with geometric and/or non-geometric (e.g. costs, time, physical properties, etc.) information - as well as data generation, exchange and processing in interdisciplinary processes (Sibenik and Kovacic, 2018). BIM and computer-aided simulations are already used in isolated cases, but there is still a lack of interoperability and data consistency. The applications are still in classical domain-specific thinking and silo attitude of the data of the different planning disciplines, resulting in information and data losses (Rahmani Asl et al., 2015). However, the goal of seamless global software interoperability is far from being achieved in AEC industry (Grilo and Jardim-Goncalves, 2010). The discrepancy between product-dependent interfaces and the resulting incomplete transfers of geometry and attributes prevent error-free data and information transfer. IFC (Industry Foundation Classes) is the most widely used scheme for integrated planning. IFC-based exchange is currently the most used standard for BIM-based data exchange, with over 150 software tools supporting the scheme (buildingSMART, 2018). The data exchange workflow using IFC building data is still sequential. However, this integrated scheme as a data management concept in AEC industry does not take into account production planning.

## 2.3 BIM in Industrial Construction Projects

Woodhead et al. (Woodhead et al., 2018) see data integration as the key factor for value creation and a need to overcome the tendency to use point solutions in construction industry. Even if there are approaches and concepts for a digital factory, holistic methods and tools, integrating production processes, machine layout and building and BSE-planning are still lacking. Since industrial construction projects are involving multidisciplinary teams and processes, the application of BIM offers a great opportunity to support integrated production and building planning (Oesterreich and Teuteberg, 2016).

However, the integration of production systems into building design possess a great challenge for BIM processes and tools (Näser and Wickenhagen, 2018). BIM application and workflows within manufacturing companies, the interfaces and the data exchange with other related departments in an industrial company have been little researched (Ma et al., 2017). An integrated model in industrial building design, which links production with building design, is recommended, but is not yet available (Kampker et al., 2013, Büscher et al., 2014). Wiendahl et al. (2014) propose the approach of "synergetic factory planning", integrating the two disciplines on process level and without using BIM. Näser and Wickenhagen (2018) investigate the integration of factory planning into building design with BIM, from production system planning perspective. Bracht et al. (2015) examine the collaboration in a virtual production project space with the aim of faster elimination of collisions, promotion of continuous communication and improvement of planning quality. The integration of the production system planning into the building design, from production planner's perspective and for the operation phase (post-planning) is conducted at TU Dortmund (Lenz et al., 2019, Delbrügger et al., 2017).

## 2.4 Computational Tools for Structural Analysis

Current tendencies in structural design point towards an increased use of BIM and parametric design tools embedded in Rhinoceros 3D platform (Associates;, 2020b) such as Grasshopper (Associates;, 2020a), Karamba3D (Preisinger, 2020) etc. next to the common analysis tools based on Finite Element Method (FEM). Most FEM-based structural analysis tools are not integrated into the BIM working environment (Hasan et al., 2019). Each analysis software has its own way of defining the analysis model, leading to many challenges in implementation of BIM in structural design, such as lack of software interoperability and data exchange problems. Despite the considerable progress in the development of open standards, software tools are still not able to provide a functional and reliable exchange between domain-specific models (Laakso and Kiviniemi, 2012). The most commonly used Open Standard for the exchange of architectural and structural models is IFC (Dib). Sibenik (Sibenik and Kovacic, 2018) evaluated BIM-based structural design and its data exchange and identified that current available certified software tools do not provide sufficient possibilities for a satisfactory data exchange as they do allow interoperability only to a limited extent. The use of BIM in early design stage is a great challenge, as it requires a high degree of explicit knowledge, which is often not available at that time. In addition, structural analysis tools are not efficient for early design stage, as their goals is on precision rather than flexibility (Rolvink et al., 2019). Parametric Modelling requires less explicit knowledge than BIM. Parametric modeling supports in the initial phase of projects, since an early integration of engineering-specific knowledge is possible (Sacks and Barak, 2008) and dynamic geometry and information descriptions by variable parameters allow fast variant studies, enabling a flexible design method and evaluation (Shea et al., 2005). However, standard parametric tools offer little information for multidisciplinary analysis and optimization in simulation-based, engineering-specific software (Pan et al., 2019, Mora et al., 2008). Parametric tools have the potential to couple BIM and structural analysis to carry out early structural performance simulations.

## 2.5 Structural Performance and Multi-Objective Optimization

Simulation-based optimization can quickly support multidisciplinary teams in the exploration of multiple design variants, as parametric design generates numerous design alternatives. However, multi-objective optimizations require maximum integration, while often the necessary interoperability of existing modeling, simulation and visualization tools is missing (Rahmani Asl et al., 2015). In order to design and optimize a structural system a number of important decisions need to be made, relating to other disciplines. However, AEC professionals generate and analyze very few design alternatives in the concept phase because of limitations in processes and software tools (Flager et al., 2009). In structural design, optimization methods are rarely carried out because they are time-consuming and inflexible. As a result, planners make decisions with little or no information about the decision's outcome and impact on the overall performance (Basbagill et al., 2017, Mueller and Ochsendorf, 2015).

Few structural analysis methods allow analysis and visualization in a single environment, provide feedback only to the structural engineer himself and do not support an integrated performance improvement (Mueller and Ochsendorf, 2015). Building geometry and construction are directly dependent on the results of the structural analysis (Schmidt et al., 2010). Current tools and processes do not support a fast generation and evaluation of multi-objective results in a structural design process or the handling is complex and error-prone (Mueller and Ochsendorf, 2015, Brown and Mueller, 2016). Furthermore, the parameter definition for the formulation of integrated evaluation criteria is difficult to assess in early design stage (Chi et al., 2015). Existing multi-objective optimization approaches are often used for customer-specific algorithms or for the optimization of single systems to generate geometric, discipline-specific parameters (Flager et al., 2009, Mueller and Ochsendorf, 2015, Brown and Mueller, 2016, Alexis Danhaive and Mueller, 2015, Gerber et al., 2014). Octopus (Vierlinger, 2019), implemented in Rhino and Grasshopper environment, allows multi-objective optimization, searching for many goals at once. The consideration of results and their effects on the overall performance over the whole building service life are often neglected in design processes. (Sanguinetti et al., 2010).

### 2.6 Integration of BIM and VR

The integration of VR into BIM hast the potential to support integrated design with real-time feedback and provide early collision checks. It can interactively simulate building-related scenarios, provide cost and resource estimates, increase communication, improve planning model verification, provide real-time feedback on interactions, and enable integration into early design stage (Rüppel and Schatz, 2011, Lin et al., 2018, Sharma et al., 2017). Numerous research focus on the use of virtual reality to accelerate the design process (Berg and Vance, 2017, Zimmermann, 2008, Whyte et al., 2000).

### 2.7 Conclusion

Building and production planning are currently not linked, so that planning is carried out in two parallel worlds. Integrated planning in industrial construction projects requires a high degree of networking, coupling and coordination of processes and sub-models of architecture, structural-, BSE- and production planning. In order to enable integrated modelling and optimization, the early use of digital design tools as well as a continuous data exchange is necessary. Especially in the early design stage, which has the greatest impact on performance in operation phase, flexibility and thus the lifetime of buildings, few holistic methods are available. Current BIM systems use simplified simulation models and lack basic requirements for early multidisciplinary decision support. Occasionally is the focus in multi-objective optimization on the structural performance, resulting in suboptimal building structures and inflexible floor plans. Structural analysis usually refers to numerical analysis, a methodology that hardly allows fast variant generation, evaluation and visualization. The use of VR with BIM is still rare in the design and execution of construction projects.

The research project BIMFlexi addresses the lack of a flexible BIM-based structural design methodology taking into account production planning and investigates appropriate multi-objective optimization methods focusing on the structural performance and visual decision support in real-time.

This paper identifies potentials and limits for integrating processes and sub-models of building and production planning and proposes a framework for a “BIM-based digital Platform for Flexible Design and Optimization of Industrial Buildings for Industry 4.0” coupling BIM, parametric tools and VR to support in early decision making to in long-term increase the buildings’ flexibility.

## 3 Research design - towards the framework

The paper builds up on the interaction of various disciplines, such as architecture, structural engineering and BSE- and production planning. Focus is on the mapping and coupling of respective discipline specific models and data in order to generate a framework for a BIM-based digital platform, which enables the integration of building and production planning and serves as a multi-objective optimization model with decision support. The proposed framework in particular addresses the structural design, as the load-bearing structure is the main obstacle to free production planning and flexibility.

In order to obtain information about the industrial software eco-systems and discipline-specific digital models, such as BIM-, structural analysis-, production planning- and VR-models, the planning processes of all stakeholders are mapped. This involves checking the individual models on respective characteristics, structure and contents, qualities, composition.

Production planning, architecture, structural and BSE- engineering are directly related, making a combination of the requirements from the as-is analysis necessary. Therefore, possible interface formats of the sub-models and software solutions are analyzed. The conducted mapping enables deriving, aggregating, evaluating and comparing the processes, sub-models, data structures and software tools, defining an integrated industrial building design process 4.0 (see Figure 2).

Succeeding the process mapping and analysis, existing parametric modeling, analysis and optimization tools such as Rhino (Associates;, 2020b), Grasshopper (Associates;, 2020a), Karamba3D (Preisinger, 2020) and Octopus (Vierlinger, 2019), are comprehensively analyzed on potentials and limits regarding interoperability and coupling ability to BIM and VR. In our future research, the interoperability of this software eco system will be tested and evaluated upon which the most favorable software constellation will be chosen.

Based on the previous process, model and data mapping and analysis the framework proposal for a “BIM-based digital platform for flexible design and optimization of industrial building for Industry 4.0” is generated, presented in the following section.

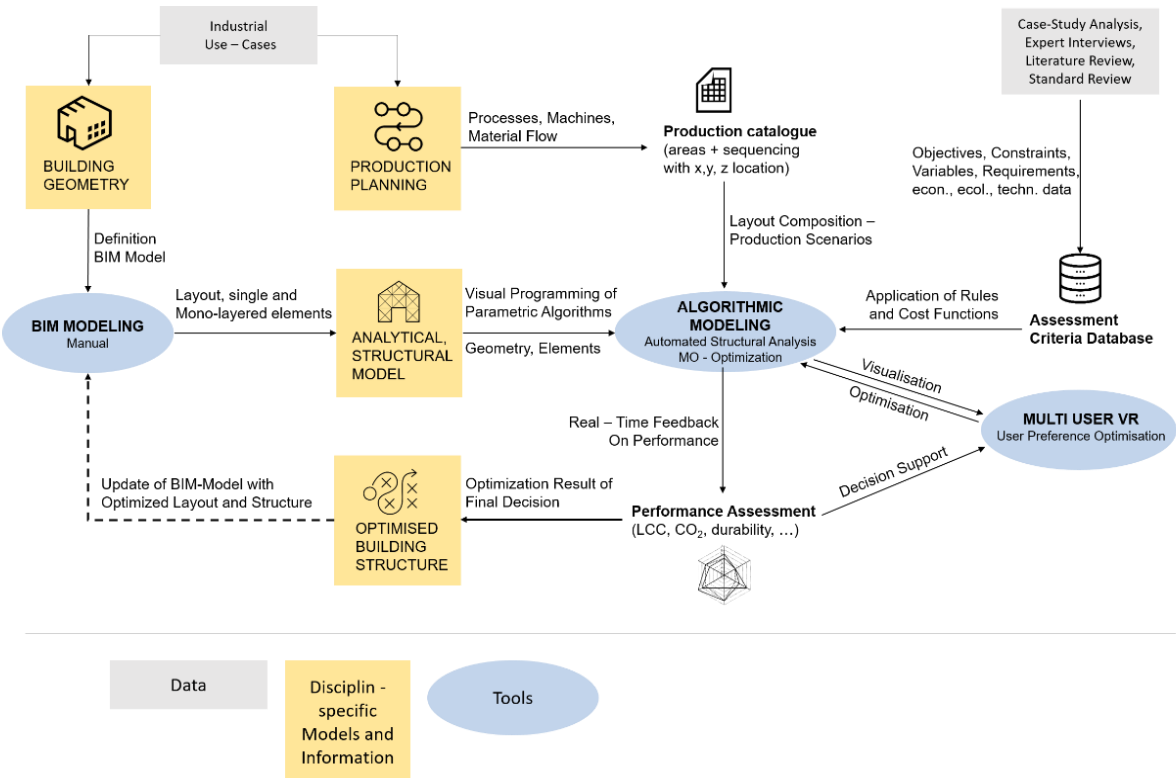


Figure 1: Research Design: Mapping the Processes, Models and Data – Integrated Industrial Building Design 4.0

## 4 FRAMEWORK PROPOSAL

The main objective of the research project BIMFlexi is to make industrial buildings of industry 4.0 efficiently adaptable to rapidly changing production processes by coupling digital planning methods (BIM, Parametric Modelling and Analysis) with new optimisation algorithms and multi-user VR, taking into account economic, ecological and technical parameters. A framework for an Integrated BIM-based Digital Platform should enable the design, structural analysis and optimization of flexible building structures and serve as visualization and decision support.

The proposed framework approaches the integration of new optimization methods into the BIM-design process, generating multi-objective optimized building structures with minimal user intervention. Furthermore, the integration of multi-user VR into the BIM environment will allow users to quickly and intuitively explore 3D-planning structures and interactively check and manipulate the design to announce their preference for additional optimization. The purpose is not to utilize existing systems and approaches per se; rather, it aims to significantly optimize the design process by integrating different existing tools in one platform.

A consistent data structuring, as basis for model integration, will enable the coupling of software-dependent (BIM software, algorithmic models and VR) and software-independent (parameters, requirements and cost functions) data, in a bi-directional data exchange manner, allowing real time feedback. This integration represents one of the major challenges, as the computational runtime should be kept to a minimum in order to enable real time feedback.

Figure 3 displays the proposed framework, which will be tested, evaluated and if necessary modified in further research. The framework consists of six main parts in the process: 1.) BIM-Model, 2.) Algorithmic Script, 3.) Structural Analysis, 4.) Database, 5.) Multi-Objective Optimization, 6.) Multi-User VR Visualization.

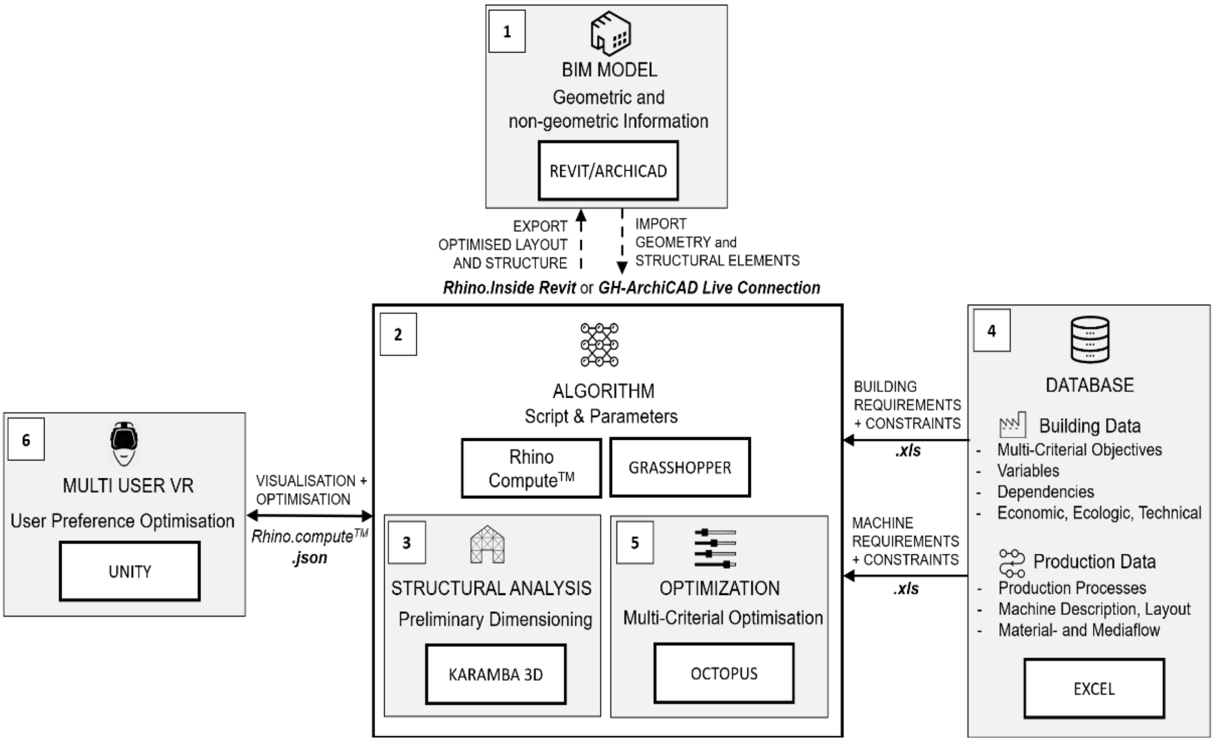


Figure 2: Framework Proposal for a BIM-based digital Platform for Flexible Design and Optimization of Industrial Buildings for Industry 4.0

*1.) BIM-Model.* A BIM-model of the industrial building will be modeled in a BIM authoring software containing information from architectural design. The BIM software will be tested and evaluated in further research. The BIM-model serves as geometric and non-geometric database. Thereby, the geometry will be pre-defined from the architect in which first assumptions like axis grid system, elements and materials are made. The created BIM-model will be linked to the algorithmic script. The necessary information for seamless data transfer and specific data exchange requirements are prepared by classifying, filtering and pre-processing the geometric and non-geometric data.

*2.) Algorithmic Script.* For flexible design, making a fast alternative generation for optimization possible, the development of an algorithmic script with linkage to the BIM-model will be proposed. Within this task, we intend to use Grasshopper as visual programming language. During the research we evaluate whether the existing tools are sufficient or if modifications and own algorithms have to be developed and implemented. From the BIM-model geometry, structural elements and pre-defined necessary data will be imported directly into the algorithmic script. Whereby, data not needed for layout and structural optimization, such as geometric elements from wall or roof cladding, will be excluded from the import. We intend to use Rhino.Inside (Associates;, 2020c) for Revit® (Inc.;, 2020) and Grasshopper - ArchiCad Live Connection (SE.;, 2020b) for ARCHICAD (SE.;, 2020a) and test whether they are suitable for bi-directional data exchange.

*3.) Structural Analysis.* In order to carry out the structural analysis we propose to extend the algorithmic script using a parametric engineering software e.g. Karam-ba3D, enabling flexible structural design on preliminary design basis. The algorithmic structural analysis script (PARAT) will automatically generate the structural analysis model based on geometries and information from the BIM-model. The analysis results will be iteratively used as input for further optimization.

*4.) Database.* Developing a comprehensive database ensures the collection of all necessary data for Building Design and Production. The building database collects parameters, constraints, objectives and variables for the structural analysis and it contains a definition of the cost function for the multi-objective optimization. Furthermore, it includes ecological, economic and technical parameters for the performance evaluation. The database for production will contain different sets of possible production layouts, defined sets of machines and their requirements to be able to simulate different production process scenarios.

*5.) Multi-Objective Optimization.* Our proposed multi-objective optimization algorithm will additionally optimize the layout of a building. The variables for layout optimization will mostly contain parameters of load-bearing structures including dimensions and positions of columns, girders, etc. Our optimization will take into consideration the result of structural analysis calculated by Karamba3D. The proposed methodology for structural layout generation is based on the combination of optimization-based and procedural techniques for content generation. The implemented algorithm will iteratively combine the procedural generation of structural elements in a building with the optimization of the layout with respect to objectives of optimization. These objectives will include the following aspects:

- Structural reliability
- Suitability for multiple production plans without the need of changing the building
- Fit with original architectural building layout
- Feedback from decision-makers using the multi-user VR visualization
- Life-cycle costs and material demand
- Other objectives including economical, ecological, technical and other factors

These factors will be combined into a common analytical cost function by scalarization. The cost function will be then optimized in a proposed hybrid optimization process. It is planned to explore the wide solution space of building layouts using genetic algorithms enriched with rule-based procedural generation. The parameters from the planning process, production planning and architectural layout will be used directly as input for the algorithm.

In each iteration of our optimization, several layout proposals will be generated which will be then analyzed in by Karamba 3D. The values from structural analysis will be then taken into account again during the optimization. The BIM-model and PARAT will therefore serve as inputs for the automatic optimization.

Finally, the proposed VR-Exploration in Unity 3D will also serve as a tool for several users to obtain the evaluation of the generated designs. Prior to this step, several proposals will be generated by our optimization and users will be able to specify their preference ratings as well as strict layout requirements in terms of spatial constraints. This user feedback can be taken into account in further optimization process.

*6.) Multi-User VR Visualization.* The goal of the multi-user VR visualization is to improve the building, resulting from our optimization, by providing the decisions and preferences about suggested layouts and positions of structural elements. These user-provided suggestions will be incorporated into further optimization process. Additionally, the proposed multi-user VR visualization will enable decision makers to make the final decision about the planning.

In order for a group of users to be able to evaluate a certain structural layout in VR, a flexible navigation method in virtual space is needed. While simple walking is often considered the most intuitive and effective way of navigation, large spatial dimensions of structural layouts in question make additional navigation methods unavoidable. Such methods supporting collaborating navigation must be developed. New methods will be based on traditional navigation techniques commonly used in VR, including combinations of teleportation and natural walking, however adopted and modified for collaborative use. Using the proposed methodology, the whole group will be able to explore the virtual environment together.

Modifications of the layouts according to user preferences will be accomplished using interaction techniques such as selection and manipulation. VR interaction encompasses a large number of methods, of which the most suitable ones will be chosen (such as ray casting with VR controllers to select objects).

The modifications in the layout performed by users will be translated into additional parameters and constrains that will be fed into the optimization process. Several layouts will be suggested to the group of users in order to select and evaluate the most suitable layout. Finally, decision makers will be able to select the best layout for their needs, the latter being stored and exported as the final solution back into the BIM model.

We intend to use existing tools and evaluate whether they are suitable and sufficient. Furthermore, we will test if the proposed coupling allows a bi-directional data transfer with minimal user invention in the workflow. The proposed framework will then be modified and, if necessary, own algorithms will be developed and implemented.

## 5 EXPECTED IMPACT AND RESULTS

The proposed framework for an Integrated BIM-based digital platform within the BIMFlexi project will introduce three additional aspects to traditional building and structural design methods, including automated layout proposals, coherence with production and real-time feedback in early design stage for decision-making.

The BIMFlexi research aims to develop a methodology for early cooperation of all stakeholders, like building owner, architecture, structural-, BSE-, and production planner, leading to an improved design process. The integration of do-main-specific processes and tools and the improved interoperability between discipline specific models is expected to minimize information and data losses, enabling a holistic improvement of the production facilities' performance.

The proposed framework is expected to improve building design processes in such a way that they better fit the long-term purpose of industrial buildings. It allows multi-objective layout and structural design optimisation, which will in-crease the building's service-life, leading to a reduction in life-cycle costs and resource consumption. Thus, the "BIM-based digital Platform for Flexible Design and Optimization of Industrial Buildings for Industry 4.0" provides useful assistance in interdisciplinary working environments.

## 6 Conclusion and future outlook

The AEC industry is slightly hesitant to implement new technologies and innovations, digitizing its value chains and processes more slowly than other industries. The perceived difficulties to digitization and thus the possibility of establishing a new culture of collaboration and exchange of digital information are mostly costs, sequential planning processes and inconsistent interfaces in software interoperability. Due to missing production system knowledge in AEC domain, digital design workflows lack integration, and existing digital design tools rarely meet the stakeholders' needs. Concluding, there is very little research of integrating production planning with BIM supported building design.

Since 80% of the life cycle costs of a building occur in the operation phase and 75% are determined in the design phase, the research project BIM Flexi ad-dresses the early design stage. In this stage, the important parameters for building performance are set and an investigation of diverse design alternatives is crucial. Several methods compose design optimizations to support integrated and performance driven design. The proposed framework of an integrated BIM-based digital platform, presented in this paper, combines BIM, parametric modelling, structural performance and VR.

In the next step of the research, a comprehensive use-case analysis, whereby real industrial projects represent the use-cases, is carried out. The use-case analysis identifies and collects building- and production-specific data and invest-gates interdependencies. Furthermore, objectives and constraints for integrated industrial building design will be investigated and the requirements and parameters for flexible and adaptable load-bearing structures examined in order to set up the database and formulate the mathematical codes for the cost function.

Based on the results of the use-case analysis and obtained data the algorithmic script for automated optimization and structural analysis will be developed. As presented in the framework, a method for linking the algorithmic script to the BIM-Model will be created. The data continuity, interfaces and suitability of the script will be tested on real industrial use-cases and an evaluation of the used tools and methods will be carried out. As soon as a reliable algorithmic script is defined, the optimization and VR integration will be taken into account.

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# AN OPENBIM BASED DATA MAPPING METHODOLOGY TOWARDS STRUCTURAL ANALYSIS USING FEM

**Fangzheng Lin[1] and Raimar J. Scherer[2]**

**Abstract:** In terms of building structural analysis, a large number of researchers throw the spotlight on data swapping from Industry Foundation Classes (IFC) models to input files from various kinds of Finite-Element-Analysis software. These attempts succeeded in accelerating pre-processing before simulation. However, the associated methodologies do not break this restriction of data-to-data mapping. Up to now, an openBIM based mapping methodology describing software-independent data mapping form an IFC model to a Finite-Element system emerges yet hardly in publications. This paper explores the theoretical possibility to automate data mapping from models standardized by IFC directly to the equilibrium equations for structural analysis with the Finite Element Method (FEM). For this purpose, a semantic model towards structural analysis using beam elements or plane elements is established to represent the topology of corresponding objects based on the data analysis result. Subsequently, the conception of data mapping is elaborated through a conceptual case study.

**Keywords:** OpenBIM, Industry Foundation Classes, Finite Element Method, Structural analysis.

## 1 INTRODUCTION

Building Information Modelling (BIM) is put forward firstly in the middle of the 20th century (Quirk 2012). This concept arises along with the ongoing digitization of the entire Architecture, Engineering and Construction (AEC) industry. Building elements and their topological relations can be semantically represented in a BIM model. For a better sharing possibility of BIM models, the initiative of openBIM was proposed by several leading software vendors (GRAPHISOFT 2020). The Industry Foundation Classes (IFC) schema developed and maintained by buildingSMART is one of the standards in the frame of openBIM, and is already widely supported by the mainstream BIM software applications (Revit, Allplan, Bently, etc.) in the field of Computer-Aided Design/Engineering. IFC standard is designed for the objective of interoperability, so that the data exchange and sharing could break through the barriers between software applications or platforms.

BIM models generated based on IFC schema are named as IFC models. This interoperability-oriented IFC models demonstrate a broad spectrum of application. Since early years of this century, the integration technology of IFC/BIM and Geo-graphic Information System has always been under development. The corresponding studied

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objects could be a single building (Thiis and Hjelseth 2008), indoor modelling (Choi et al. 2008), urban management (Yamamura et al. 2017), etc. In the domain of Facility Management, IFC also becomes a popular topic for more convenient data acquisition and more effective object visualization (Fu et al. 2006). Internet of Things is dedicated in information communication. In terms of its implementation, Motamedi et al. demonstrated the applicability of the proposed method using IFC and Radio Frequency Identification through a real-world case study (Motamedi et al. 2016).

Besides the proceeding research work, BIM oriented simulation known as BIM2SIM is of concern, as well, for the researchers trying to broaden the application domains of IFC. Andriamamonjy et al. proposed a work flow to filter the information from related building elements out, and to convert them to structure data files for the engine of Building Energy Performance Simulation (Andriamamonjy et al. 2018). For certain energy simulation software, an interface could be programmed to automate the data exchange from an IFC model to an input file (Ahn et al. 2014). Similarly, Dimyadi succeeded in transforming an IFC model to an input file for fire and smoke simulation (Dimyadi et al. 2008).

As a matter of fact, the core of so called simulation is numerical computation using Finite-Element-Method (FEM), which can serve not only for thermal calculation (e.g. energy simulation) and fluid dynamics (e.g. fire simulation), but also for structural analysis. Romberg et al. attempted transforming slabs and columns from an IFC model to a FEM model mesh by solid elements (Romberg et al. 2004). Hu et al. completed a data ex-change mechanism from IFC models to several input models from FEA software and among these input models (Hu et al. 2016). The concept Building information modelling ought to specifically refer to buildings, however, the idea of information modelling has been extended to infrastructures as the representative of other structure categories. Stascheit et al. studied the data requirements in simulating a conventional tunnel structure in an open source simulation framework and competed the data mapping from an IFC tunnel model to the input model in pre-processing of FEA software (Stascheit et al. 2013). The alike data exchange work flow was also preliminary automated by Hamdan for a bridge project (Hamdan 2018).

So far, the majority of articles corresponding to BIM2SIM threw light on information transformation from corresponding building elements in IFC building models to the input files of simulation software. Each kind of simulation software has its own modelling philosophy and a specific compiler to make its simulation engine understanding the input files. Due to these reasons, related methodologies can only be implemented separately with certain software. By means of that, the simulation engine developed obeying the principle of FEM is barely touched during the procedure of model transformation. Therefore, it makes sense to bridge the gap directly between IFC models and the bottom algorithm of FEM (Figure 1).

The above mentioned issue of hereby the focus of this paper. The data architecture of IFC models for structural analysis is requested to be analysed. An equilibrium equation system using FEM needs to be established and the data requirements equation system should be investigated. Through a conceived semantic model and a conceptual case study, the FEA-software-independent data exchange process is discussed and implemented.

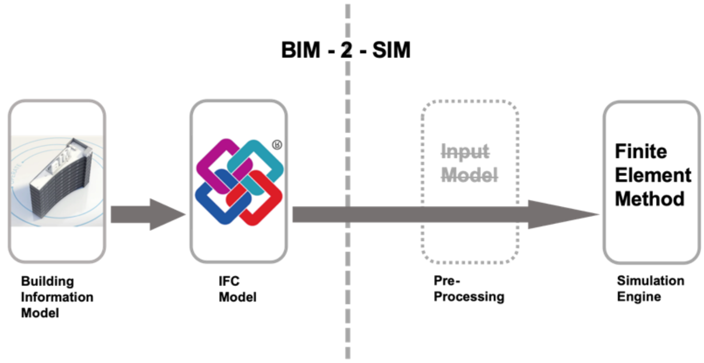


Figure 1: The proposed data mapping conception

## 2 Analysis of IFC Standard

For the purpose of data swapping in this paper, the domain of structural analysis in IFC standard and the related IFC objects will be studied. The essential entities for structural analysis was defined by the completed IAI project "ST-4" (Weise et al. 2003), emerged intuitively in IFC 2×2, and has been inherited to the current IFC version (IFC 4). Figure 2 demonstrates typical IFC objects/entities for structural analysis. While IFC curve members represent columns, walls and slabs are defined as surface elements. It is not demonstrated in Figure 2, but reasonable to infer that curve members and surface members can also respectively instanced though beams and plates. A complete structure is usually assembled by several kinds of structural elements, thus the continuity between these elements are implemented by connection definition including point connection and curve connection. This connection definition also belongs to element coupling from the point of view of FEM. In this section, the data structure of related building elements and element connection are requested to be investigated.

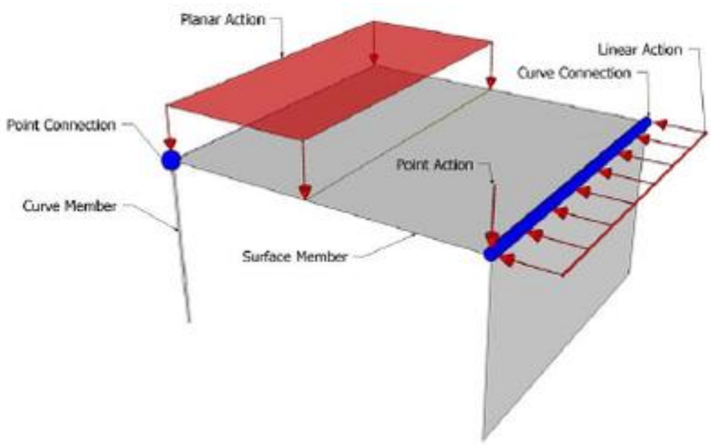


Figure 2: Visualization of a typical structural analysis model from IFC (buildingSMART 2020a)

### 2.1 Building Objects

#### 2.1.1 Beam and Column

Beams and columns are usually meshed by beam elements in structural analysis. Considering the features of beam elements, the essential information that IFC models are capable to deliver to the equilibrium equation of structural analysis encompasses Young's modulus $E$, length of beam element $l$ and moment of inertia $I$. $E$ is a constant designated in the model attribute of material; $l$ indicates the offset of cross sections' sweep or extrusion that can be simply obtained from coordinate values in IFC models; $I$ as one of cross section geometric coefficients must be calculated based on the given cross section profile. In view of modelling building beams or columns according to IFC standard, the proceeding required information originate from the two objects namely axis and profile. Therefore, the definitions corresponding to both objects in IFC standard are analysed.

As the domain of structural analysis in IFC standard states, beams and columns belong to the entity IfcStructuralCurveMember. Figure 3 and Figure 4 illustrate the data architecture of axis and profile definitions. The entity IfcEdge, composed of a starting IfcVertexPoint and an end IfcVertexPoint, serves for axis modelling of the related IfcStructralCurveMember. IfcVertexPoints are quantified through 3D coordinates contained by IfcCartesionPoints. IfcDirection indicates vectors from the starting point to the end point. IfcMaterial is the entity, where material names and parameters can be designated through property sets based on IFC standard. IfcProfileDef is a super-type of all definitions of standard and arbitrary profiles, the entity is used to define a standard set of commonly used section profiles by parameters or explicit curve geometry (buildingSMART 2020b). The majority of typical profile categories for steel and reinforced concrete structure are included among the sub-types of IfcProfileDef, e.g. IfcRectangle-HollowProfileDef, IfcRectangleProfileDef, IfcIShapeProfileDef, IfcTShapeProfileDef, etc.

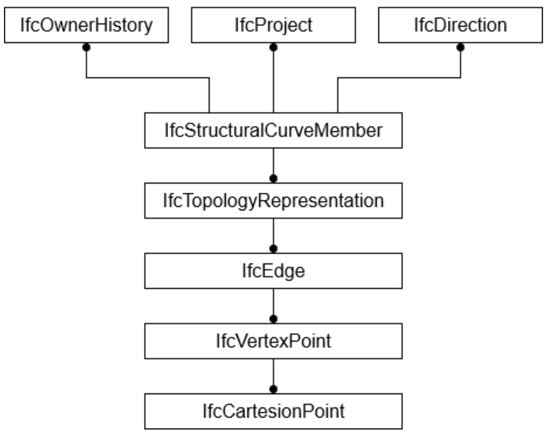


Figure 3: Referenced entities for axis definition in IfcStructuralCurveMember

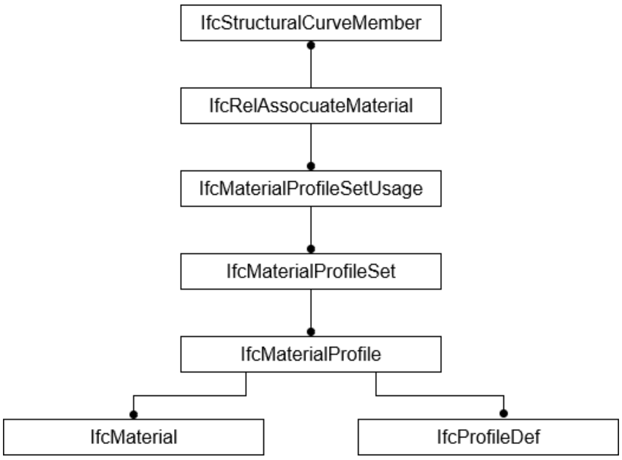


Figure 4: Referenced entities for material and profile definition in IfcStructuralCurveMember

### 2.1.2 Wall, Plate and Slab

Under the definition of IfcStructuralAnalysisModel, the plane building elements such as walls, plates and slabs are represented by IfcStructuralSurfaceMember that is a proper sub-type of IfcStructuralMember (buildingSMART 2020b). Unlike IfcStructuralCurveMember, in terms of structural analysis, data structure of the semantic model of IfcStructuralSurfaceMember consists of geometric definition (Figure 5) and material definition (Figure 6).

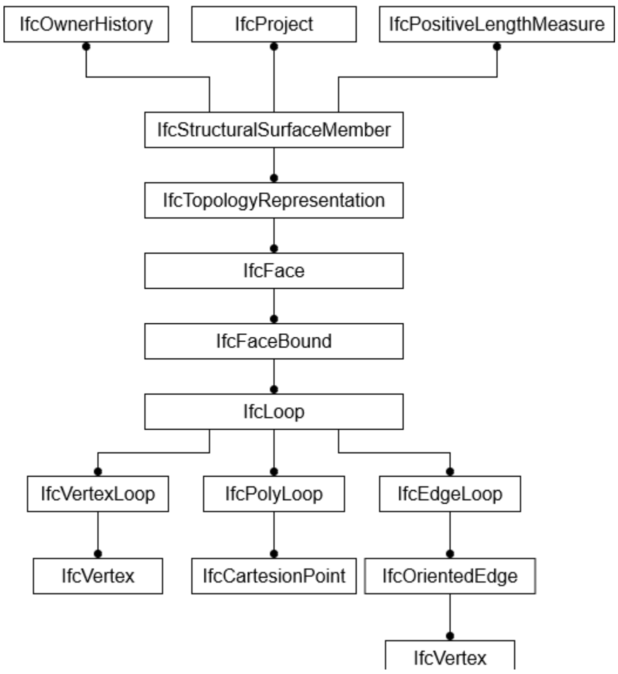


Figure 5: Referenced entities for geometric definition in IfcStructuralSurfaceMember

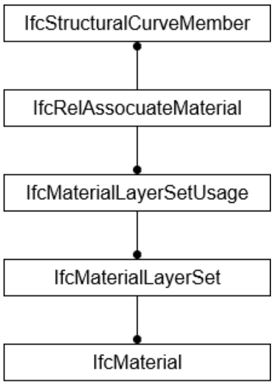


Figure 6: Referenced entities for material definition in IfcStructuralSurfaceMember

## 2.2 Connection

### 2.2.1 Point Connection

Point connection is realized through vertexes, it contains the coupling among curve members (beams and columns) or between curve members and surface members (walls, plates and slabs). The date structure of IfcStructralPointCnnection is illustrated in Figure 7. IfcVertextPoint storing global coordinates is referenced by IfcStructralPointoCnnection through IfcProductionDefinitionShape and IfcTopologyRepresentation. The point connection and the affiliated structural elements are separately objects defined in IFC, the entity IfcRelConnectsStructuralMember is applied to bridge the relation between these two objects. If a connection point defined by IfcStructralPointoConnection functions as a support, the connection then needs to be referenced to IfcBoudnaryNodeCondition, where 6 degrees of freedom in the 3D coordinate system are defined.

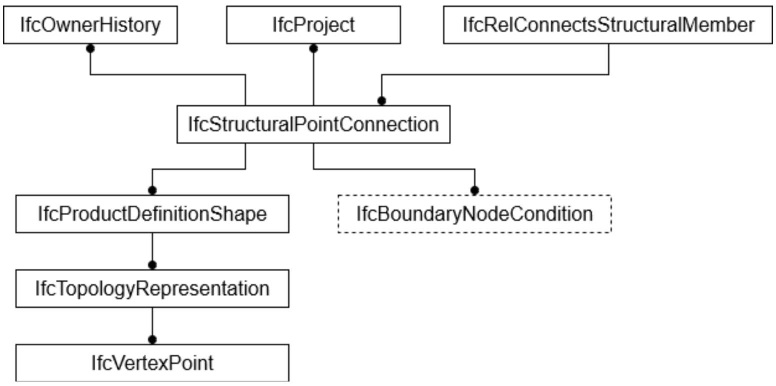


Figure 7: Referenced entities of IfcStructuralPointConnection

### 2.2.2 Curve Connection

The occurrence of curve connection exists in the shared edges of different surface members. Analogous to point connection, curve connection using IfcStructural-CurveConnection (Figure 8) comprises shape definition (IfcProductDefinitonShape) and boundary condition (IfcBoundaryEdgeCondition). The shared edge geometry is provided by IfcEdge composed with a starting and an end vertex. In a support point, 6 degrees of freedom can be either fixed or released in IfcBoundaryNodeCondition. The curve

connection and its belonging structural members are required to be topologically referenced through IfcRelConnectsStructuralMemeber
as well.

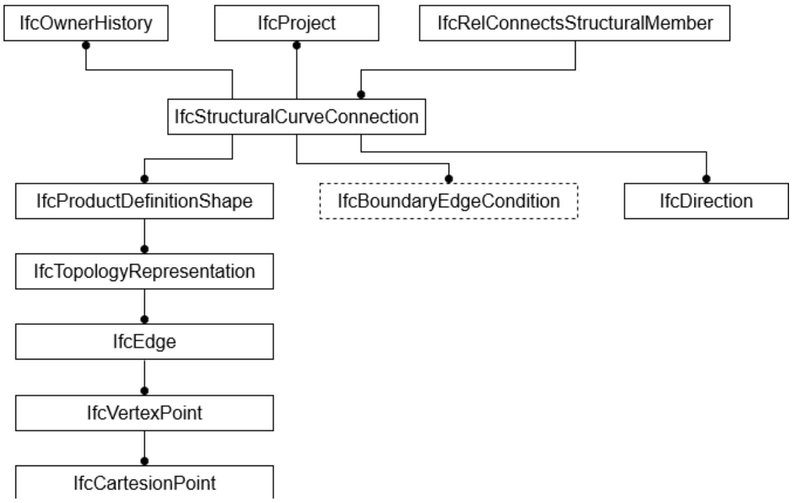

Figure 8: Referenced entities of IfcStructuralCurveConnection

# 3 Finite-Element System Establishment

Generally, structural analysis contains static analysis and dynamic structural analysis. The governing numeric stiffness equation for static acting forces is

$$\boldsymbol{K} \cdot \boldsymbol{u} = \boldsymbol{f}, \#(1)$$

whereas the latter is numerically modelled through the motion (equilibrium) equation

$$\boldsymbol{K} \cdot \boldsymbol{u} + \boldsymbol{D} \cdot \dot{\boldsymbol{u}} + \boldsymbol{M} \cdot \ddot{\boldsymbol{u}} = \boldsymbol{f}. \#(2)$$

With respect to both equations, stiffness matrix K and mass matrix M are sup-posed to be of major concern during data mapping. The damping matrix is in this research work omitted by reason of its complexity, which needs a separate paper to be developed properly. Considering that this paper concentrates on beam elements and surface elements, this section is dedicated to elaborating how a global stiffness matrix or a global mass matrix is established. Through investigating the derivation process of these two element matrices, the data requirements can be obtained for the purposed of semantic modelling towards structural analysis.

## 3.1 Beam Element

### 3.1.1 Element Matrices

Bernoulli-Euler Beam (Gavin 2018) is a classical and widely used hypothesis neglecting shear deformation and rotatory for beam element in structural analysis. A thin beam with a small cross section satisfies the principle of Bernoulli-Euler Beam. In a spatial coordinate system, each node of a beam element owns 6 degrees of freedom (Figure 9) including deformation along x-axis (stretching), rotation around x-axis (torsion), deformations along y- and z-axis (deflection) and rotations around y- and z- axis (bending). Equation (3) and Equation (4) show the definition of an element stiffness matrix $\boldsymbol{K_e}$ and an element mass
matrix $\boldsymbol{M_e}$ in a 3D coordinate system:

$$\boldsymbol{K}_e = EA\int_0^l \varphi'_x\,\varphi'_x\,dx + EI\int_0^l \varphi''_y(x)\,\varphi''_y(x)dx\,\#(3)$$

and

$$\boldsymbol{M}_e = \rho A\int_0^l \varphi_x\,\varphi_x\,dx + \rho A\int_0^l \varphi_y(x)\,\varphi_y(x)\,dx\,,\#(4)$$

$E$ indicates Yong's modulus, $A$ area of element cross section, $I$ inertia moment and $l$ element length. Linear shape functions $\varphi_x$ is in the integration of the first term referring to stretching, Hermit-Polynomial serves as shape functions $\varphi_y$ in the integration of the second item about bending and torsion. One node has 6 degree of freedom, one beam element has 12 degree of freedom, thus an element matrix ought to have a size of 12×12.

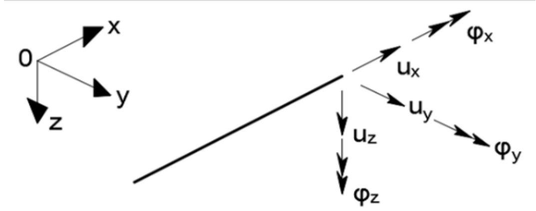


Figure 8: Six degrees of Freedom of a beam element in the 3D coordinate system

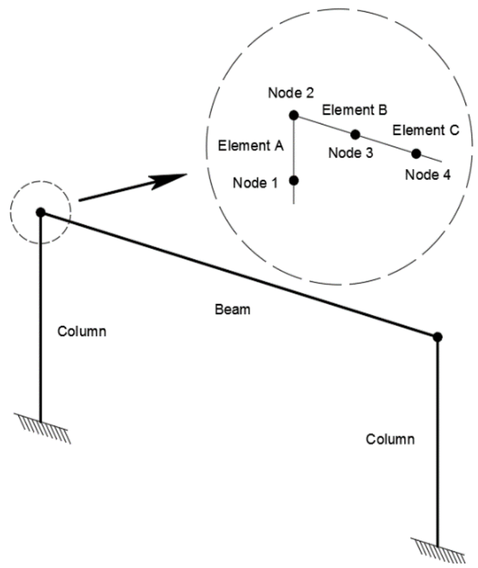


Figure 10: A frame with detail drawing at a connection part

### 3.1.2 Global System

As the detail drawing in Figure 10 illustrates, continuous modelling and coordinate transformation form a local and a global system are two issues in beam system construction. Adjacent beam elements are connected through shared nodes, this kind of connection is not only geometrical, but also material and mechanical. In the composite stiffness matrix of Element B and C (Figure 10) is represented in Equation (5); likewise, the corresponding mass matrix is established in the same way. The corresponding parameters of both elements are located at the position of Node 3.

$$K/M = \begin{bmatrix} |Node\ 2\ (Elem.B)| & 0 & 0 \\ 0 & \begin{vmatrix} Node\ 3\ (Elem.B) + \\ Node\ 3\ (Elem.C) \end{vmatrix} & 0 \\ 0 & 0 & |Node\ 4\ (Elem.C)| \end{bmatrix}\#(5)$$

For a single column or a beam, all the interconnected beam elements are usually oriented to the same direction. However, in a more complicated structure like a frame composed by a beam and two column (Figure 10), Element A and Element B are perpendicular to each other, so that a simple overlapping of elements and nodes is not sufficient. As a consequence, the local coordinates of elements ought to be transformed to match the global coordinate system. The spatial transformation of a beam element is completed by rotations around the three axes in the global coordinate system. In Figure - 11, the beam element needed to be transformed is firstly rotated around z-axis from Equation (6), then y-axis from Equation (9), and eventually x-axis from Equation (10). The rotation angles $\varphi_z$ and $\varphi_y$ can be obtained by the nodal coordinates of an element, $\varphi_x$ is the rotation around x-axis, which is not in relation to the coordinates, but should be given externally, in the case of beam elements.

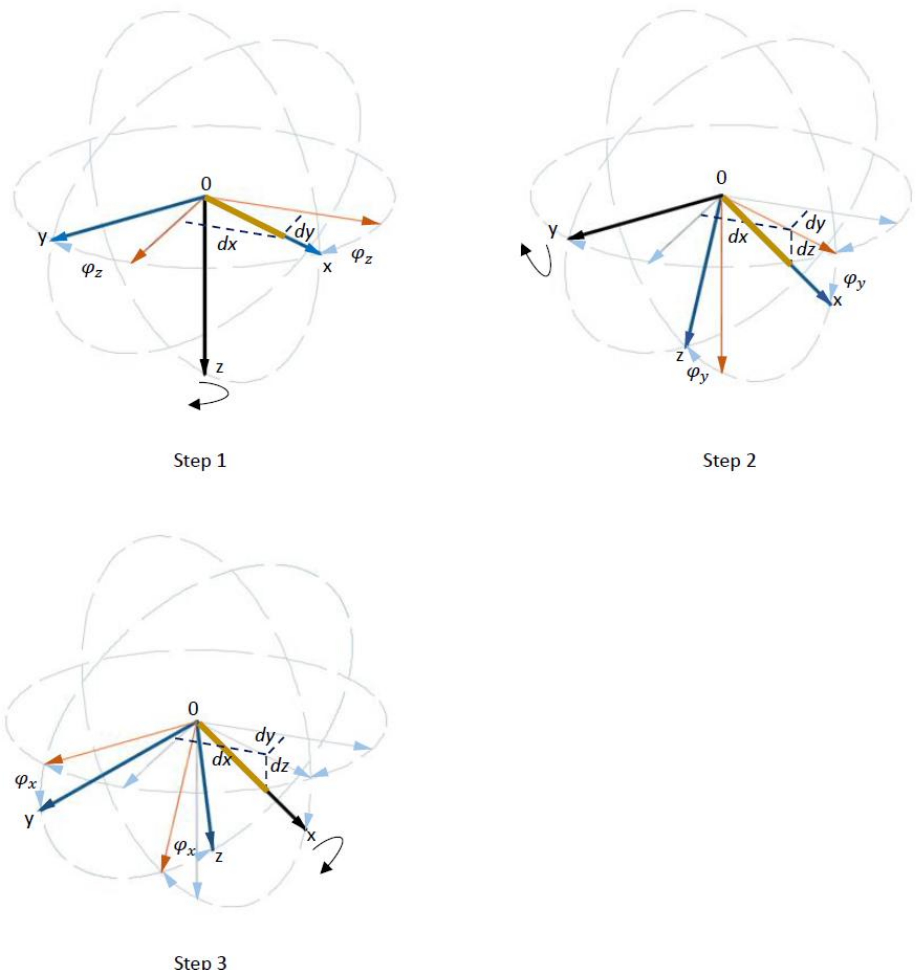


Figure 11: Coordinate transformation steps

$$t_z = \begin{bmatrix} \cos(\varphi_z) & -\sin(\varphi_z) & 0 \\ -\sin(\varphi_z) & \cos(\varphi_z) & 0 \\ 0 & 0 & 1 \end{bmatrix} \#(6)$$

$$\varphi_z = \arctan(dy/dx) \#(7)$$

$$t_y = \begin{bmatrix} \cos(\varphi_y) & 0 & \sin(\varphi_y) \\ 0 & 1 & 0 \\ -\sin(\varphi_y) & 0 & \cos(\varphi_y) \end{bmatrix} \#(8)$$

$$\varphi_y = \arctan\left(dz/\sqrt{(dx)^2 + (dy)^2}\right)\#(9)$$

$$t_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi_x) & -\sin(\varphi_x) \\ 0 & \sin(\varphi_x) & \cos(\varphi_x) \end{bmatrix}\#(10)$$

The element transformation matrix $\boldsymbol{T}_e$ from Equation 12 is, therefore, obtained from Equation (7), Equation (9) and Equation (11), and brought in to address this issue.

$$t = t_z \cdot t_y \cdot t_x\#(11)$$

$$\boldsymbol{T}_e = \begin{bmatrix} t & 0 & 0 & 0 \\ & t & 0 & 0 \\ & & t & 0 \\ sym & & & t \end{bmatrix}\#(12)$$

## 3.2 Surface Element

As a matter of fact, the principle of surface finite element shows a more convoluted situation than beam element. Typical finite element types contain plane element, plate element and shell element, the complexity of the three element rises in turn. In addition, for a rectangular surface element, which is one of the most usually used surface element types for a regular-shape surface structural element is generally defined by 4 nodes. More nodes can be applied in surface element definition, which leads to a higher accuracy, but cause more complex element matrices and a larger and hence more expense in computing time. Triangular elements utilized widely for irregular-shape structural elements also share the identical features. Plane elements (Figure 12) can be employed to mesh a wall model, nevertheless is not suitable for slab and plate models that are usually meshed by finite plate or shell elements. This paper merely focuses on plane elements, other kinds of finite surface element will not be discussed.

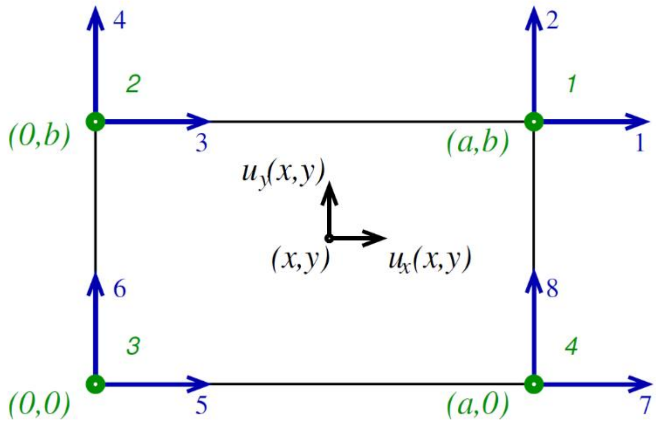

Figure 12: 2D rectangular element coordinates and displacements (Gavin 2018)

Under the basic assumption that the plane with uniform thickness are isotropic and homogeneous, a plane element is classified as plane-stress element or plane-strain element, according to their constitutive relationship. Both of the relation functions $\boldsymbol{S}_{p\sigma}$ and $\boldsymbol{S}_{p\epsilon}$ , can be substituted in the numeric expression of element stiffness:

$$\overline{\boldsymbol{K}}_e = \int_A [\boldsymbol{B}(x,y)^T\, \boldsymbol{S}(E,\upsilon)\, \boldsymbol{B}(x,y)]\, h\, dx\, dy\, ,\#(13)$$

And element mass:

$$\overline{\boldsymbol{M}}_e = \int_A \rho\, [\boldsymbol{\Psi}(x,y)^T\, \boldsymbol{\Psi}(x,y)]\, h\, dx\, dy\, ,\#(14)$$

where $\overline{\boldsymbol{K}}_e$ indicates the plane element stiffness matrix, $\overline{\boldsymbol{M}}_e$ the plane element mass matrix, $h$ the uniform thickness, $\boldsymbol{S}$ the elastic relationship, $\boldsymbol{B}$ and $\boldsymbol{\Psi}$ are shape functions (e.g. linear functions, Hermite polynomials, etc.) for plane elements, in order to obtain the element matrices.

Two points are necessary to be emphasized. First off, plane elements are merely feasible for the surface elements under the loads parallel to the plane based on the original definition. In terms of surface building or structural elements, vertical walls satisfy the condition considering geometry and load directions, but sloping walls are not suitable for plane elements anymore. Secondly, the stiffness and mass matrices will have a size of 8×8, since then deformation of planes are limited on the 2D plane. In a 3D coordinates system, where each node has 6 degrees of freedom, the element matrices are extended to a size of 24×24 for the purpose of coupling between plane elements and beam elements.

## 4 SEMANTIC MODELLING

The instructions presented here have been used to structure this paper. In Figure 13, the semantic model towards structural analysis is illustrated by the Unified Modelling Language (UML), the UML diagram takes solely beam element and plane element into consideration, in addition it generically represents the topological relationship of them. According to the basic definition, one element has at least two nodes, conversely one node regarded as a coupling connection can be shared by several elements.

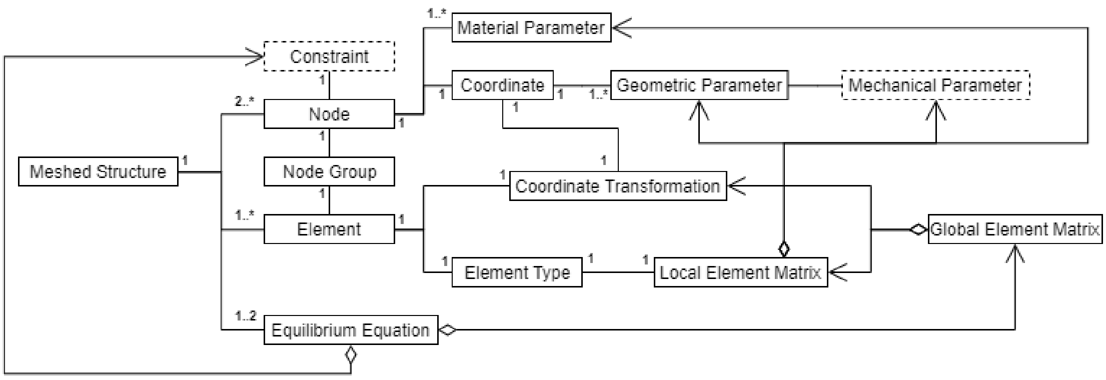


Figure 13: UML diagram of semantic model towards structural analysis using FEM

An element type (Figure 13) has two levels, the first level is dedicated to shape description of a finite element; the second implies the mathematical assumptions of finite elements, e.g. Bernoulli-Euler theory and Timoshenko theory for beam elements. Both layers lead directly to the definition of different terms in the local element stiffness and mass matrices. The nodal parameters includes material, geometrical and mechanical parameters, local coordinates and boundary conditions. They are all classified under the class Node in Figure 14. Geometrical parameters resulting from node coordinates contribute to calculate the material parameters. The boundary condition at the related node contains the states (fixed or released) of 6 degrees of freedom. Coordinate transformation is classified as an attribute of finite elements. Node coordinates are applied to obtain the spatial inclination angles of a finite element on three planes (x-y plane, y-z plane and x-z plane) in a 3D coordinate system. After deriving the local element matrices and transformation matrix, the global element matrices and successively the global matrices of the whole structure are able to be established.

## 5 Conceptual Case Study

In order to verify the feasibility of proposed data mapping methodology, a beam model is discussed in this section as a conceptual case study. Figure 14 illustrates the required IFC entities and the semantically modelled objects for structural analysis to reflect the data flow during mapping.

IfcCartesianPoints serve as vertexes composing a beam structure. Coordinates in class Node (Figure 13) are utilized to locate elements and define their geometry. IfcDirection indicates the order of IfcCartensionPoints and successively nodes of finite elements. According to that, the class Node Group is assigned, so that classes Element and Node can be instantiated. Material parameters such as Yong's modulus stored in the entity IfcMaterial are mapped to the nodal Material Parameters. Mechanical Parameter of cross section of beam elements can be designated by the values from the entity IfcProfileDef, or derived directly based on the measure of cross section, which should be automatically attached through referenced entities of IfcProfileDef, when an IFC model is exported from a BIM software application. The attributes defined in IfcBoundaryConidtion referring to constraints in FEM can be converted to the numeric representationof degrees of freedom at nodes. Eventually, the data obtained from the IFC model is employed to establish the stiffness and mass matrices (Section 3) for the purpose of structural analysis.

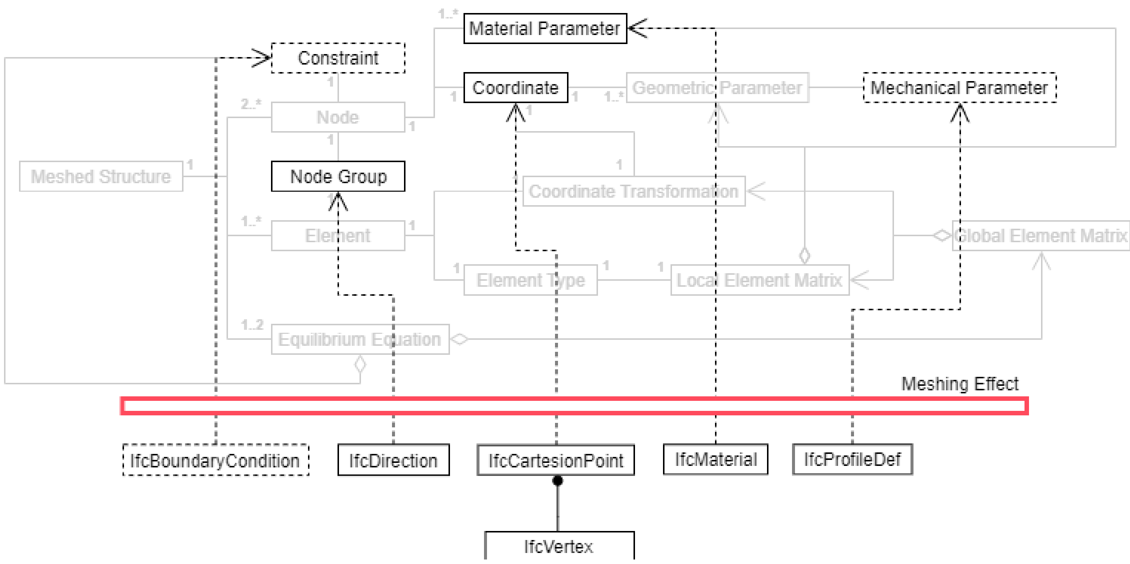


Figure 14: UML diagram of data mapping between an IFC model and the semantic model

## 6 Conclusions

This paper presents an overview of data application from IFC models with various application domains and addresses a specific concern in the field of structural analysis. A methodology is conceived to map data from IFC models to FE systems for structural analysis. Data architecture of IFC standard is analysed to comprehend modelling philosophy in the domain of structural analysis. Concurrently, data requirements of FE equilibrium equations are also studied in order to construct a topological representation semantically between structures, finite elements, nodes and the related parameters. The semantic model shows a relatively generic schema for beam elements and surface element. Focusing on beam structures, the proposed data mapping methodology is implemented with a conceptual case study, where the meshing effect is beard in mind, to bridge the gap between an IFC mode and the finite element system. Since this paper presents a theoretical research work, the methodology is expected to be enriched towards data mapping for other kinds of beam elements and surface element in future work.

## 7 Acknowledgments

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# BAS DATA STREAMING FOR SMART BUILDING ANALYTICS

**Tony Misic[1], Sara Gilani[2] and J.J. McArthur[3]**

**Abstract:** Many existing and new buildings are equipped with building automation system (BAS). BAS-integrated sensors continuously monitor environmental conditions, energy use, HVAC and lighting systems, and occupancy in buildings, collecting vast amounts of data that can be of great value for building performance optimization from both the energy use and occupant comfort perspectives. However, the heterogeneity and volume of these data pose significant barriers to their use. For the effective analysis of the collected BAS data to facilitate actionable use of them and support smart buildings, advanced analytics methods such as artificial intelligence should be deployed in real time or near real time, requiring a coherent data management strategy (streaming, pre-processing, and structuring) and integration with advanced analytics techniques. A case study whereby BAS data are collected in an academic building in Toronto, Canada, is streamed to a cloud-hosted research platform Using the BACnet software, data acquired by various sensors are collected by a BAS and streamed as tuples through a Virtual Private Network (VPN) to the cloud using Transmission Control Protocol/Internet Protocol (TCP/IP) packet messages to ensure information security. The destination of the information was an ElasticSearch (ES) cluster, which is also used as a search and analytics engine on the back end. The data streaming, pre-processing, and structuring into an ontology to support facility management and complex event processing is described in this paper along with insight regarding the stakeholder planned uses and expected benefits.

**Keywords:** Data Streaming, Building Automation, Cloud Computing.

## 1 INTRODUCTION

"If you can't measure it, you can't improve it." – Peter Drucker

Building energy consumption is poorly understood, with many not achieving their expected energy performance (Fedoruk, et al., 2015; Mallory-Hill & Gorgolewski, 2018); discrepancies between simulated (design-phase models) and measured energy use can range as high as 70-80% (De Wilde, 2014; Menezes, et al., 2012). The use of IoT devices has significantly improved this precision, for example (Kim, et al., 2015; Zibin, et al., 2016). The value of building monitoring is well-established to maintain efficient building operation. Beyond simple monitoring, machine learning predictive analytics offer significant benefit to facility owners and operators to anticipate significant issues. For example, equipment performance can be identified tracked through online fault detection and diagnosis (FDD) (Lan & Chen, 2007; Li & O'Neill, 2018) and can inform preventative

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maintenance or planned replacement, increasing system life (Beghi, et al., 2016). Energy efficiency can also be improved using strategies such as model predictive control and online commissioning; Smart and Continuous Commissioning (SCCx) has demonstrated significant potential for energy management, but commercial applications are limited (Verhelst, et al., 2017).

While also controlling equipment using prescriptive logic, Building Automation Systems (BAS) allow building operators to review the performance of individual systems while alerting them to alarms. Together, these control and monitoring functions work to ensure smooth functioning of the building. At present, most BAS software lacks the ability to perform the complex analysis necessary for FDD and SCCx, instead displaying only alarms and trends, and even "Smart" building systems available commercially are primarily limited to data mining and historical analysis. As such, a separate analytics platform is necessary to support these more complex applications, particularly for buildings with legacy systems. This paper responds to this need by presenting an approach for data ingestion and pre-processing of data streamed from a traditional BAS. The implementation details are presented as both a generalized approach as well as applied to a large mixed-use building on a university campus, which opened in Fall 2019. The planned analytics and expected stakeholder benefits are also discussed.

## 2 BACKGROUND

A BAS consists sensors, actuators, and controllers on a dedicated network. Local equipment controllers (field controllers) constantly monitor sensor (point) values and, at either a prescribed change-of-value (COV) threshold or sampling frequency, sends updated point values through a branch of the BAS (trunk) to their respective network device (network automation engine) to the central BAS workstation. To facilitate the connection of a large number of devices, open protocols – most notably BACNet IP (ASHRAE, 2005) – are used to communicate between the BAS and third-party equipment. From the field controllers to the central workstation, proprietary protocols are typically used for communication along a dedicated network. A sample portion of a typical network architecture is shown in Figure 1.

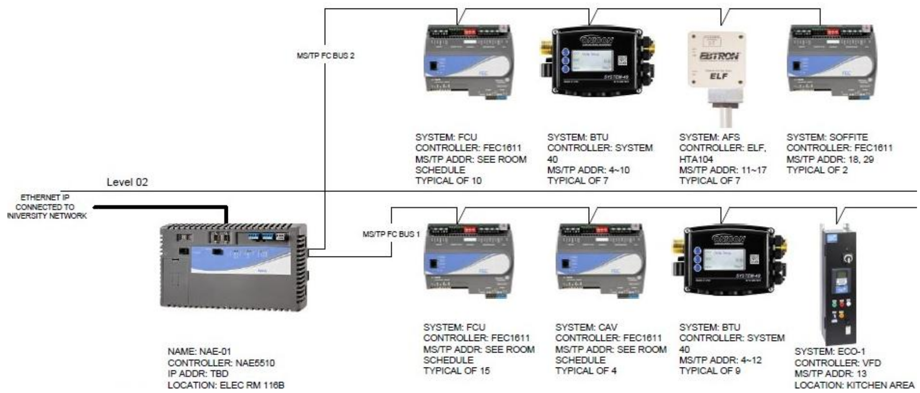


Figure 1 Example of a portion of a BAS architecture [12]

With the advent of IoT, there has been a significant interest in data streaming from sensor networks, for example (Ramprasad, et al., 2018), as well as the type of summary information relevant to the FM-BIM (Kassem, et al., 2015). The use of streamed BAS data for predictive analytics requires several key scientific challenges to be overcome: (1)

developing data definitions and structure; (2) development of a robust and secure approach for streaming the high-volume and heterogeneous BAS data; (3) development of metrics and key performance indicators; and (4) the training and implementation of analytics algorithms to monitor and calculate these metrics. The first two elements are within this paper's scope and key literature is summarized here.

Two approaches are used to structure data from sensor networks: linked data, and ontologies. Linked data stores individual the data from individual points separately, relying on an external software such as BIM to integrate this data into a common environment. Ontologies provide robust data structures and several broad ontologies have been developed to integrate BAS and IoT data (Bajaj, et al., 2017; Bhattacharya, et al., 2015), however these require that the BAS integrate significant semantic tags, which has yet to be implemented in the majority of systems.

Python scripts are widely used for computer networking applications due to its simplicity in coding and human interpretation, allowing complex or tedious network tasks to be automated quickly. Writing to an ElasticSearch (ES) cluster provides the end-user with flexibility in data interpretation. No extra interpretation must be written after processing, saving both time and resources. Furthermore, ES has multiple libraries in multiple languages, allowing for accessibility and scalability in future uses. One drawback is the indirect approach to using ES and the overhead computation when streaming into the cluster.

Cybersecurity is an increasing concern within the building sector, particularly for IoT applications as each new device provides a new potential point of entry for a data breach or cyberattack. BAS have traditionally not been designed to consider data security, relying instead on their presence on closed networks (Peacock, 2014). By breaching this network to permit streaming to an analytics server, vulnerabilities are introduced into this system that remain an open problem to be addressed, particularly given the high level of trust and limited data integrity checks inherent in these systems (Baig, et al., 2017).

# 3 Implementation

There are five components in the data streaming architecture: the BAS itself, a custom script developed in collaboration with the controls vendor to read the (proprietary) BAS network data and export it as text, a Python server to pre-process the data, the VPN connection, and the ES Cluster where future analytics will be performed.

## 3.1 Data Acquisition

There are two components in the data acquisition system: the BAS, and the software used to extract the BAS data and export it in a non-proprietary format. BAS systems vary by vendor, but typically follow the standard architecture described in Section 2.

It is critical to avoid overloading the BAS network with queries from the streaming system as this could result in lag on critical controls or – in the worst case – a BAS network failure. To avoid this, the BAS data acquisition must be a read-only system that 'sniffs' the data as it travels across the network and records it in the desired format. Unless this is done downstream of each field controller where BACNet IP is used for communication with individual equipment, this will be encoded in the proprietary BAS system, requiring coordination with the controls vendor to obtain a 'back door' to output these values in a pre-agreed, parsable text format. In this approach, COV outputs are embedded into the Data field (TCP body message) of one or more TCP packets (Fig. 2). The remainder of packet information is populated using standard TCP protocol rules (Dordal, 2014) and the completed packet is sent to the location coded into each packet to the Python server via the internal network. TCP does not permit confirmation to be sent unless all data is received in the correct order (Dordal, 2014), thus ensuring data integrity through the streaming process.

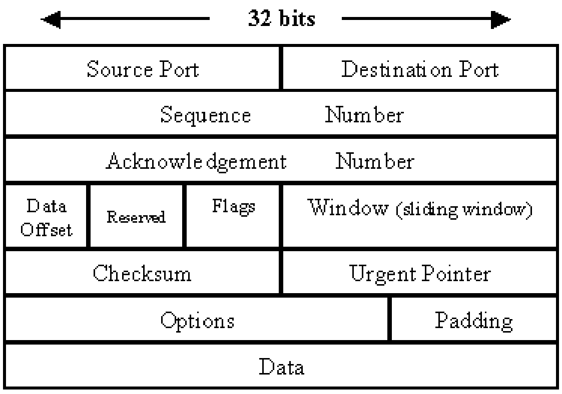



Fig. 2. TCP packet structure (Salomon, 2006)

## 3.2 Data Streaming

Data-streaming TCP packets is done through a running Python script on a physical machine located on the BAS ethernet network that points to an ES cluster index. This is shown schematically in Figure 3.

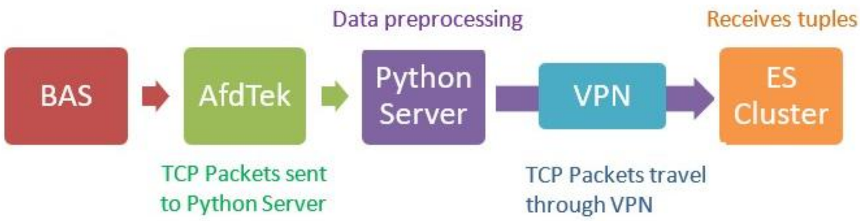



Fig. 3. Schematic of data streaming architecture from BAS to ES Cluster.

Python is used to create an indirect line of communication from the BAS to ES via the VPN, while also pre-processing the data. While the direct connection of the BAS head-end to the cloud is preferable from a reliability standpoint as it eliminates a potential point of failure – for example risk of disconnected cables, power failure at this intermediate computer, or system restarts – this permits a one-way connection from the BAS to the cloud, which is desirable from a facility management standpoint as it minimizes the risk of cyberattack. To ensure the system security on the BAS, we use a one-way output on the physical machine connected to the network. This only allows confirmation packets to come through the port securing the physical machine against attacks against its output port. This can lead to some lagged results but the information is eventually sent and therefore not a large issue. Further, this is configured as a one-way (read-only) connection at the cloud to further mitigate intrusion risk.

The script is assigned a predetermined IP address and port and that location information is inputted into the BACnet UI. The COV data sent by the BAS network devices to the Python server script, extracted from the TCP body message, and parsed using the .split and .strip functions in Python to populate a tuple consistent with the streamed data requirements discussed previously. Once the tuple has been populated with the appropriate values, the script attempts to write the data into the ES cluster index. Three means are used to avoid data loss. First, the IDs of the documents in the index are an Md5 hash (Salomon, 2006), a type of cryptographic key, is generated at each push attempt, minimizing the chance of duplicate ID's and avoiding non-duplicate data writing. Second, a backup file is written to each time a push attempt fails. In the process of writing from the file, indexing to ES is verified. This technique eliminates the loss of data during a downtime of the ES cluster or a client/server error. Finally, the entire server/client system is run over TCP/IP, which will guarantee information security and will not receive any incomplete data. Cybersecurity is enforced with a VPN, which connects the physical machine to the ES cluster.

### 3.3 Data Pre-Processing

The ES cluster will permit the structuring and pre-processing of data prior to storage in the data lake and facilitate queries by the future analytics. ES is extremely flexible, more so than SQL databases, and can be used it as a backend for a search engine, database, and analytics engine.

BAS point naming conventions, particularly in legacy systems, are frequently a) not human-readable, b) indicate the system and equipment measured but not the network location, or c) indicate the network location of the point but not the equipment or system being measured. To overcome this, a linked data approach is used to increase the context of each point the network location (NAE, trunk, and field controller), system and equipment identity, and point type information. This is achieved through a python script that calls a lookup table containing this data alongside the data point, adds it to each data instance tuple, and then parses the data to permit it's mapping to the data structure. By mapping the full context (unique) points, only a single search is necessary, and parsing is achieved by the structuring of the lookup tables.

Two nomenclatures are used to record the sensor network topology. A network context nomenclature in the form NAEDeviceID.TrunkID.FieldControllerID.PointType and a system context nomenclature that can be readily mapped to a FM-enabled BIM (as the third field is the host family instance) and asset management database in the form BuildingID.SystemID.EquipmentID.PointType.

## 4 Case Study

The Daphne Cockwell Health Science complex (Fig 4).is a mixed-use building consisting of a 16,300m2 (175,000sf) academic podium that is primarily lab space and academic offices with 19-storey residence tower housing 332 student rooms in 2- and 4-bedroom apartments. Developed by the university to be a 'living lab', the building "contains a comprehensive sub-metering system that collects real-time data about energy consumption and climate control. The data can be used to identify opportunities to improve sustainability and inform decisions for future buildings, as well as being used for graduate-level research" (Ryerson University, 2019).


Fig. 4. Daphne Cockwell Complex at Ryerson University (Perkins + Will, 2019).

As noted, a 'back door' was implemented by the controls vendor (Johnson Controls Inc.) in collaboration with a subconsultant (AFDTek), permitting output of the timestamp, full-context point name, and value in text (TCP message) format from the BAS head-end. As noted in the literature review, the selection of TCP/IP for communication ensures data integrity, while the Md5 hash identifier prevented duplicate data.

System security is vital to the architecture avoiding cyberattacks on the host network and cloud and this was a key concern of the University. To address this, a secure VPN connection to a dedicated ES Cluster was used, configured to only permitting only the confirmation of TCP packet arrival to be sent back to the Python server (Fig. 5), to minimize the risk of cyber-intrusion. Figure 6 shows a sample of the same data as received by the ES Cluster.

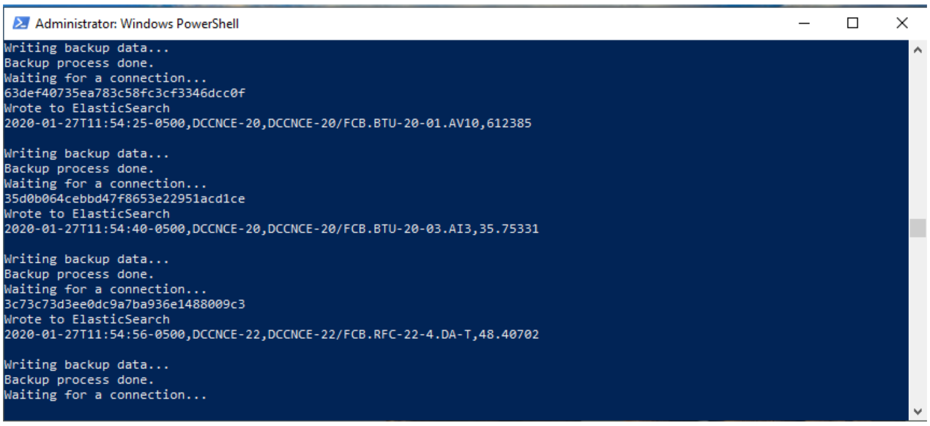
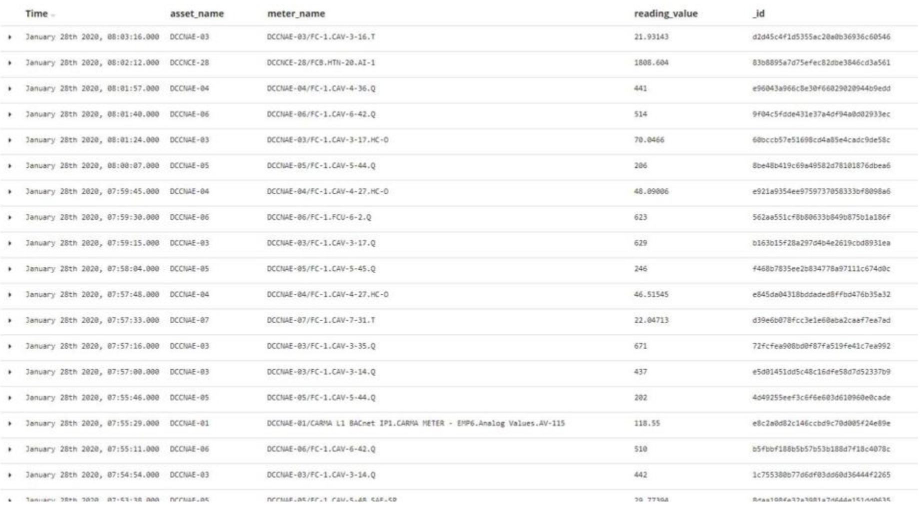



Fig. 5. Window showing data streaming to ES server via VPN



| Time | asset_name | meter_name | reading_value | _id |
|---|---|---|---|---|
| January 28th 2020, 08:03:16.000 | DCCNAE-03 | DCCNAE-03/FC-1.CAV-3-16.T | 21.93143 | d2d45c4f1d5355ac20a0b36936c60546 |
| January 28th 2020, 08:02:12.000 | DCCNCE-28 | DCCNCE-28/FCB.HTN-20.AI-1 | 1808.604 | 83b8895a7d75efec82dbe3846cd3a561 |
| January 28th 2020, 08:01:57.000 | DCCNAE-04 | DCCNAE-04/FC-1.CAV-4-36.Q | 441 | e96043a966c8e30f66029020944b9edd |
| January 28th 2020, 08:01:40.000 | DCCNAE-06 | DCCNAE-06/FC-1.CAV-6-42.Q | 514 | 9f04c5fdde431e37a4df94a0d02933ec |
| January 28th 2020, 08:01:24.000 | DCCNAE-03 | DCCNAE-03/FC-1.CAV-3-17.HC-O | 70.0466 | 60bccb57e51698cd4a85e4cadc9de58c |
| January 28th 2020, 08:00:07.000 | DCCNAE-05 | DCCNAE-05/FC-1.CAV-5-44.Q | 206 | 8be48b419c69a49582d78101876dbea6 |
| January 28th 2020, 07:59:45.000 | DCCNAE-04 | DCCNAE-04/FC-1.CAV-4-27.HC-O | 48.09006 | e921a9354ee9759737058333bf8098a6 |
| January 28th 2020, 07:59:30.000 | DCCNAE-06 | DCCNAE-06/FC-1.FCU-6-2.Q | 623 | 562aa551cf8b80633b849b875b1a186f |
| January 28th 2020, 07:59:15.000 | DCCNAE-03 | DCCNAE-03/FC-1.CAV-3-17.Q | 629 | b163b15f28a297d4b4e2619cbd8931ea |
| January 28th 2020, 07:58:04.000 | DCCNAE-05 | DCCNAE-05/FC-1.CAV-5-45.Q | 246 | f468b7835ee2b834778a97111c674d0c |
| January 28th 2020, 07:57:48.000 | DCCNAE-04 | DCCNAE-04/FC-1.CAV-4-27.HC-O | 46.51545 | e845da04318bddaded8ffbd476b35a32 |
| January 28th 2020, 07:57:33.000 | DCCNAE-07 | DCCNAE-07/FC-1.CAV-7-31.T | 22.04713 | d39e6b078fcc3e1e60aba2caaf7ea7ad |
| January 28th 2020, 07:57:16.000 | DCCNAE-03 | DCCNAE-03/FC-1.CAV-3-35.Q | 671 | 72fcfea908bd0f87fa519fe41c7ea992 |
| January 28th 2020, 07:57:00.000 | DCCNAE-03 | DCCNAE-03/FC-1.CAV-3-14.Q | 437 | e5d01451dd5c48c16dfe58d7d52337b9 |
| January 28th 2020, 07:55:46.000 | DCCNAE-05 | DCCNAE-05/FC-1.CAV-5-44.Q | 202 | 4d49255eef3c6f6e603d610960e0cade |
| January 28th 2020, 07:55:29.000 | DCCNAE-01 | DCCNAE-01/CARMA L1 BACnet IP1.CARMA METER - EMP6.Analog Values.AV-115 | 118.55 | e8c2a0d82c146ccbd9c70d005f24e89e |
| January 28th 2020, 07:55:11.000 | DCCNAE-06 | DCCNAE-06/FC-1.CAV-6-42.Q | 510 | b5fbbf188b5b57b53b188d7f18c4078c |
| January 28th 2020, 07:54:54.000 | DCCNAE-03 | DCCNAE-03/FC-1.CAV-3-14.Q | 442 | 1c755380b77d6df03dd60d36444f2265 |

Fig. 6. Raw storage of events as recorded on ES Cluster

In this case study, the streamed data output from the sniffer is in the format {Timestamp, NAEID, full context point name, value}. The full context point name in this instance is the network context point name described previously. Adding the system context point name was performed using a lookup table (Table 1). This system context point name is used internally on the BAS and uses the nomenclature BuildingID.SysID.BASID.PointID. For monitored equipment, the SysID is the building system containing the equipment, for example, the chilled water system, and BASID is the actual equipment being controlled, for example a chiller or chilled water pump. For room-based points, SysID is assigned "RM" and BASID is the room number, thus permitting a consistency in nomenclature that facilitates parsing into the SQL database. Taking in the formatted data a pre-processing Python script maps each column from the given data to the system context point IDs, which map each sensor, actuator, and controller to the appropriate equipment and system as well as network location.

Table 1. Lookup Table (selected rows)

| Network Context PointID | System Context PointID |
|---|---|
| DCCNAE-01/FC-1.CAV-1-10.CLGUNOCC-SP | DCC.RM.DCC01-13.CLGUNOCC-SP |
| DCCNAE-01/FC-1.CAV-1-10.EFF-OCC | DCC.RM.DCC01-13.EFF-OCC |
| DCCNAE-01/FC-1.CAV-1-10.EFFCLG-SP | DCC.RM.DCC01-13.EFFCLG-SP |
| … | … |

This system is being used to develop Continuous Commissioning and online optimization algorithms for deployment in the DCC building, in collaboration with the Facility Engineer. The scope of these planned algorithms includes online optimization and control of equipment and systems, for example predicting the ideal chilled and condenser water temperature setpoints to minimize chiller system energy consumption, and fault detection and diagnosis, for example tracking chiller fouling.

## 5 Discussion and Conclusions

This paper has presented a standard approach to data acquisition from a building automation system, which could be applied to any IoT sensor network, and the necessary processing required to structure and stream this data. This approach has been applied in a large academic building with over 10,000 BAS points and has demonstrated itself to be robust in implementation.

This approach has significant value to support Smart Continuous Commissioning and other online controls optimization efforts. While advertised by many vendors, existing BAS "smart" analytics capabilities are limited to data visualization and the few vendor solutions available require additional investment beyond the cost of the BAS Moreover, this functionality is typically a "black box" application where the Facility Engineer can neither inspect the algorithm to understand what is being considered and how the controls are being changed as a result. As was the case in this study, such an approach can result from a lack of trust in these applications. An open analytics system, on the other hand, addresses these issues of transparency while also providing the Facility Engineer with flexibility in modifying these to better suit their unique needs.

The streaming of BAS data facilitates several other valuable stakeholder activities. For example, this data can be readily mapped into an FM enabled BIM, where it can be overlaid with data integrated from other FM systems such as preventative maintenance, space management, call center logs and document complaints, building inspection records, et cetera. The nomenclature presented, whether built into the BAS naming conventions for new systems or added to the streamed data during pre-processing, further supports FM-enabled BIM by embedding significant semantic information regarding system and sensor network architecture to each point. For buildings where no BIM readily exists, a lightweight FM-enabled BIM can be rapidly developed (for example, using the approaches presented in (McArthur & Bortoluzzi, 2018; Bortoluzzi, et al., 2019)), and this information can be mapped to the equipment to quickly add the building systems topology.

The presence of building identification tags for the data supports multi-building contexts, ensuring unique point identifiers across campuses and building portfolios, and thus enabling the nesting or linking of multiple FM-enabled BIMs to generate full-site visualizations.

The primary limitation of this paper is that only a single implementation has been tested. Use a specific system, the JCI medicine system and made use of a vendor provided back door to access the text data. An equivalent means of of sniffing the change of value data from another BAS is necessary for the supplementation.

Future work will include the development of key performance indicators for the facility and their optimization. For example, the first priority KPI to be developed is chiller plants energy consumption, and the next stage and the first set of analytics to be developed will monitor the chiller system infer its performance and required characteristics and identify the optimal controls points to minimize system use chiller energy use.

## 6 Acknowledgments

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# FROM FORECASTING TO REAL-TIME PROCESS CONTROLLING WITH CONTINUOUS SIMULATION MODEL UPDATES

**Yara Salloum[1], Annika Jodehl[2], Markus Thewes[3] and Markus König[4]**

**Abstract:** Simulation models become widely used in the industry as they can provide a good prediction of a project's performance to support planning and decision-making. Process simulation is particularly interesting in mechanized tunneling projects, where processes interact very sophisticated. The productivity of such projects does not only depend on the performance of the main production processes, but is also significantly influenced by the performance of logistics and maintenance processes. In the planning phase, it is essential to analyze different supply systems and provide a detailed evaluation of them. So far, the simulation models developed are mainly used during the planning phase. However, during the execution of the project many parameters deviate from their predicted values and are subjected to uncertainties and unforeseen events that could not be considered beforehand.

Hence, it is essential to be able to update the simulation model at different stages of the project to get a new prediction of the project performance and to enable an online-steering of the logistics processes. This paper proposes a method to perform a so-called continuous-update of a simulation model, including the validation of the implemented concept to proof that the validity of the online simulation model is maintained.

**Keywords:** process simulation, mechanized tunneling, integration of real-time data, online simulation.

## 1 INTRODUCTION

Tunnel constructions are important infrastructure projects for enhancing transportation networks in congested and fast-growing cities. These projects have usually long durations and large budgets due to their complexity, risks and uncertainties. In general, the conventional methods of tunneling have fewer processes, which make it easier for planning with traditional construction techniques such as preceding diagram method (PDM), critical path method (CPM), program evaluation and review techniques (PERT) or line of balance method (LOB) (Abdalla & Marzouk, 2013).

This planning process is more complicated in mechanized tunneling projects because of the complexity of the supporting systems of the tunnel boring machine (TBM). The productivity of tunneling projects does not only depend on the TBM performance, for

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example its advance speed, penetration rate or the machine capacity, but subsequently also on the performance of the supporting logistics. These processes, such as the supply chain of the required materials or the transportation systems inside the shaft and the tunnel, can significantly affect the project performance. Any delay or failure in the sequence of processes can delay or stop the tunnel excavation and segmental lining. For the above-mentioned reasons, it is necessary to develop higher sophisticated simulation models, to simulate the interaction and overlapping between these simultaneously operating tasks to predict the progress of the project.

The use of simulation models is currently limited to the planning phase. However, the tendency to use such models as a decision-making tool during the execution phase supports the need to develop dynamic simulation models (Adra, 2016). For this, real-time data needs to be integrated into the model at any stage of the simulation to have a continuous update of the simulation outputs, and an updated prediction of the project performance, especially when unexpected disturbances occur (Law, 2009).

This study presents a concept to update an agent-based simulation model focusing on logistics in a slurry shield tunneling project. This concept is performed in four basic steps to adjust the offline simulation model so that the integration of real-time data at different stages of the simulation is enabled and it conducts suitable validation tests to ensure the validity of the online-simulation model.

## 2 Background

In this section, a general overview of the main processes in mechanized tunneling is given and followed by a summarized description of the agent-based model that is used in this study to simulate these processes. A short overview of the development of the online simulation modeling is also included as a background for the presented method for the real-time simulation of the described processes.

### 2.1 Processes in mechanized tunneling

Mechanized tunneling is a highly automated process for the construction of tunnels. With the help of tunnel boring machines (TBM) it is possible to excavate large diameters up to 19 m. For tunnelling in soft ground, mainly shield machines are used. These shield machines are surrounded by a cylindrical steel construction, the shield, which supports the excavated cavity until the final tunnel lining is installed (see Fig.1). In a shield machine the soil is excavated by a large cutting wheel and brought to the surface by pipes or transport vehicles. The installation of the tunnel lining takes place alternately to the excavation of the soil. In the protection of the shield skin, pre-cast concrete segments, the segmental lining, are assembled to a ring and installed as a permanent support of the tunnel cavity (Maidl, et al., 2014).

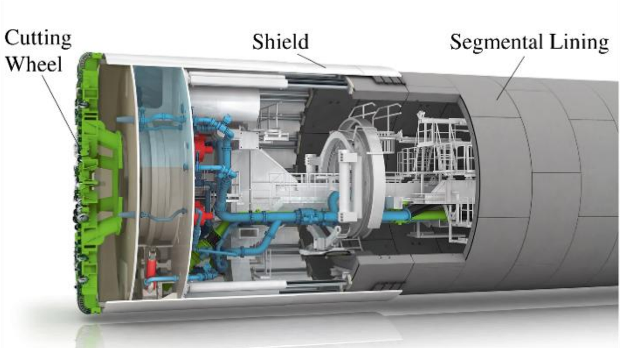


Fig. 1. Construction of a Shield Machine (Mix shield) (Herrenknecht AG)

All types of TBMs have in common, that there are trailing support decks known as the back-up system inside the finished part of the tunnel. The support system located on the back-up includes conveyors or other systems for muck removal, slurry pipelines if applicable, control rooms, electrical systems, dust removal, ventilation and systems for transport of pre-cast segments (Maidl, et al., 2014).

Disturbances in the process flow are unavoidable in the field of mechanized tunneling, but it is necessary to identify sources of interference and minimize them wherever possible. Disturbances occur both in the area of propulsion and in the area of logistics. Often, downtimes caused by failures are representing more than 40% of the total project time (Duhme, 2018).

Rahm (2017) defines seven possible causes for disturbances in mechanized tunneling. These include:

- Difficult geological conditions
- Extension of supply lines, pipes, and tracks
- Maintenance work
- Technical failures
- Inefficient, congested or sensitive logistics processes
- Modification of the machine and logistics elements
- Exceptional events

## 2.2 Description of the Simulation model

Simulation models are composed of elements that display the elements of a real system. Depending on the subject to be analyzed, the systems are simplified. For this research, an agent-based simulation model for a mechanized tunneling project including the logistics operations is used. The model is implemented in the software Anylogic (The Anylogic Company, 2019), which is a java-based multi-method simulation framework, which uses Discrete Event Simulation.

The proposed concept to update simulation models in this study is applied to this model. The model consists of 22 agents. Each agent presents one element of the TBM and the jobsite logistics. Figure 2 illustrates the block definition diagram of this agent-based model.

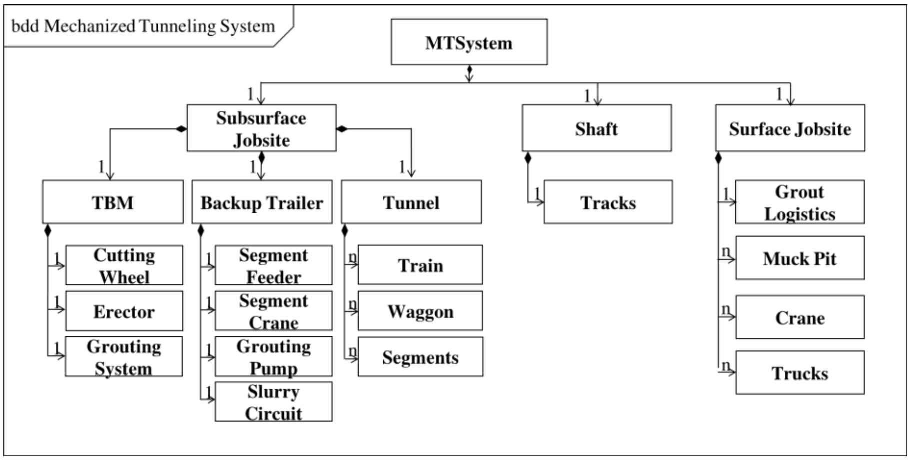

Fig. 2. Block definition diagram of the studied mechanized tunneling simulation model

The three agents of the first level represent the three main areas of a mechanized tunneling project (the subsurface jobsite, the shaft and the surface jobsite). The agents in the second level represent the processes taking place in each area. Thus, the cutting wheel, the erector and the grouting system are the main elements of a TBM.

Agents operate in a discrete manner, but they interact with each other through signals and messages to communicate and mimic the interaction of the real system. In addition, each agent contains of various parameters, variables and statecharts. Parameters describe the main properties of the simulated process, such as capacities and properties of the equipment and machinery or initial flow rates of pumps. Statecharts describe the state of an element and define the conditions under which a state is changed. The variables, however, are used to store the state of an agent.

## 2.3 Real-time update of Agent-based Simulation models

The evolution of simulation tools has been driven by the rapid evolution of computing technologies. As computing technologies have decreased in cost and increased in performance, the capability of simulation tools to solve increasingly complex problems in less time has improved.

In the last few years a lot more studies followed, which aimed to develop simulation models for mechanized tunneling projects (e.g. AbouRizk et al. (2011)). First models were developed in CAD and 3D modeling software mainly to simulate the boring process and the cutting wheel. Kasper et al. (2004) presented a 3D finite element model of shield-driven tunnel excavation in soft ground. This model considers the main factors that control and affect the excavation process such as the soil and the ground water, the frictional contact of the boring machine to the soil, the hydraulic jacks, the tunnel lining and the tail void grouting.

Liu et al. (2010) presented another simulation model for hard rock TBM using the CYCLONE framework. The processes are modeled on a rather abstract level but involve interactions between on-site logistics and production processes by taking into account the disposal of muck. The authors identify a suitable logistic setup through variation of three parameters: muck cars per train, number of trains and rail infrastructure. Until then most models are isolated and presented on one level of the process without taking into consideration the influence of other processes in different layers of the project such as supporting logistics operations and maintenance.

Rahm et al. (2013) suggested an approach to simulate the TBM machines and the progressing rate of the machine, taking into consideration the disturbances and investigating the effect of technical failures related to the process. A jobsite logistics simulation was presented by Scheffer et al. (2014), which focuses on the supply chain of a tunneling project. This model connects the operations on surface with the subsurface processes and allows interactions in between.

As noticed in the tunneling projects, a high percentage of delays in project's execution occur due to delays and disorder in logistics and supply chains. Because of that, a lot of studies were more focused on the simulation of logistics and maintenance. In 2017 Rahm investigated disturbances in the logistic chain of mechanized tunneling projects with the help of process simulation (Rahm, 2017). In 2018, Duhme (2018) analyzed the simulation based planning of logistics processes in mechanized tunneling. Besides, Conrads et al. (2018) investigated a detailed simulation of the maintenance strategies considering various wear prediction models for cutting tools in order to suggest an optimal maintenance plan for the TBM.

Simulation models developed in these researches contain many non-deterministic variables (i.e. the variables that present the frequency of the failure's occurrence in the operating equipment and the duration of required maintenance). These uncertainties are usually displayed by distribution functions.

The recent studies of process simulation modeling of construction and production systems suggest that models should be data-driven during the simulation. Data-driven simulations are common in mathematical models but their applications to agent-based models are not technically mature yet. However, the integration of real-time data into simulation models enables the possibility of comparing simulations to the real system during the project's execution. The incorporation of real-time data into agent-based models improves the predictive ability of such models and results in increasingly well-calibrated model parameters and more accurate outcomes (Oloo & Wallentin, 2017).

The most essential step to manage the online-update of the simulation system is the effective management of the simulation inputs, which means the ability to update the inputs of the model at any time. In agent-based models, each agent operates in a discrete manner, using the parameters and variables implemented in the agent. The initial values of these variables are defined at the beginning of the simulation run and the simulation starts to operate from this state to the specified endpoint sequentially in a state based order until a break- or end-state is reached. It is important to ensure that the interaction between the agents is not disturbed by the change of the initial state of the variables. However, the main challenge in the update process is to maintain the validity of the model after the update in order to ensure that the model is still working properly after the new implementation. Although the agents are isolated during execution, to implement the update, extra variables or time-related functions need to be added, which may require a validation step afterwards.

## 3 METHODOLOGY

Following, a method to update a computer agent-based simulation model to predict the overall project duration and the interaction between the different production, logistics and maintenance tasks in TBM tunneling projects is presented. The main concept of the online update of a simulation model can be summarized in four basic steps, which are illustrated in Figure 3.

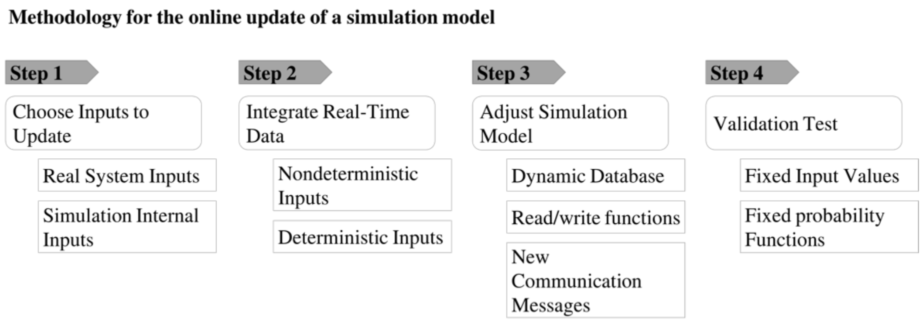


Fig. 3. The methodology suggested to update an ABM simulation model Implementation

First, the main input parameters must be identified that affect the objective of the simulation the most (step 1). These input parameters can be classified into two main types. The first type are the real-system inputs, such as the specifications and capacities of the equipment. The second type are the internal simulation inputs, which have been added by the designer to store values during the simulation and to regulate the flow of the processes during the execution of the simulation. The second step is to integrate the real-time data in the simulation model (step 2). In TBM simulation models, a large number of inputs have a non-deterministic nature, for example, they don't have a fixed value but they are randomly predicted by mean of probability distribution functions (PDFs). For the deterministic inputs, the integration in the model's database is simple and direct. In contrast, the integration of non-deterministic inputs requires extra analysis and comparison between the real-time data and the data gatherd from similar previous projects to update the predefined probability distribution functions.

If the model is designed for offline simulation during the planning phase, some modifications might be necessary for the next step to adapt the real-time data for an online update of the simulation model (step 3). The first adjustment is to create a dynamic database for the inputs of the process. The input's database contains the initial values and states of the elements variables. Other modifications might be also necessary to collect and insert data at different stages of the model execution. The last step includes the validation of the implemented concept, taking into consideration the nondeterministic nature of the simulation variables, to ensure the credibility of the modified model (step 4).

This process can turn the offline simulation model into a useful tool to support the decision-making process during the execution of the project.

## 3.1 Identifying the essential input parameters for the online-update

Since the focus of this study is on the overall project duration and the performance of the logistic processes on the construction site, the simulation parameters and variables that control these processes must be investigated.

The project duration is related to the core processes of excavation, ringbuild and the performance of the supporting processes. On top of that, the duration of the project's downtime is related to the technical failures of each process and the subsequent delay in the logistics supplies. To monitor these variables in each agent, their initial values are connected to the input database. Figure 4 illustrates the main five agents in the simulation model and a sample of the connected variables to the database.

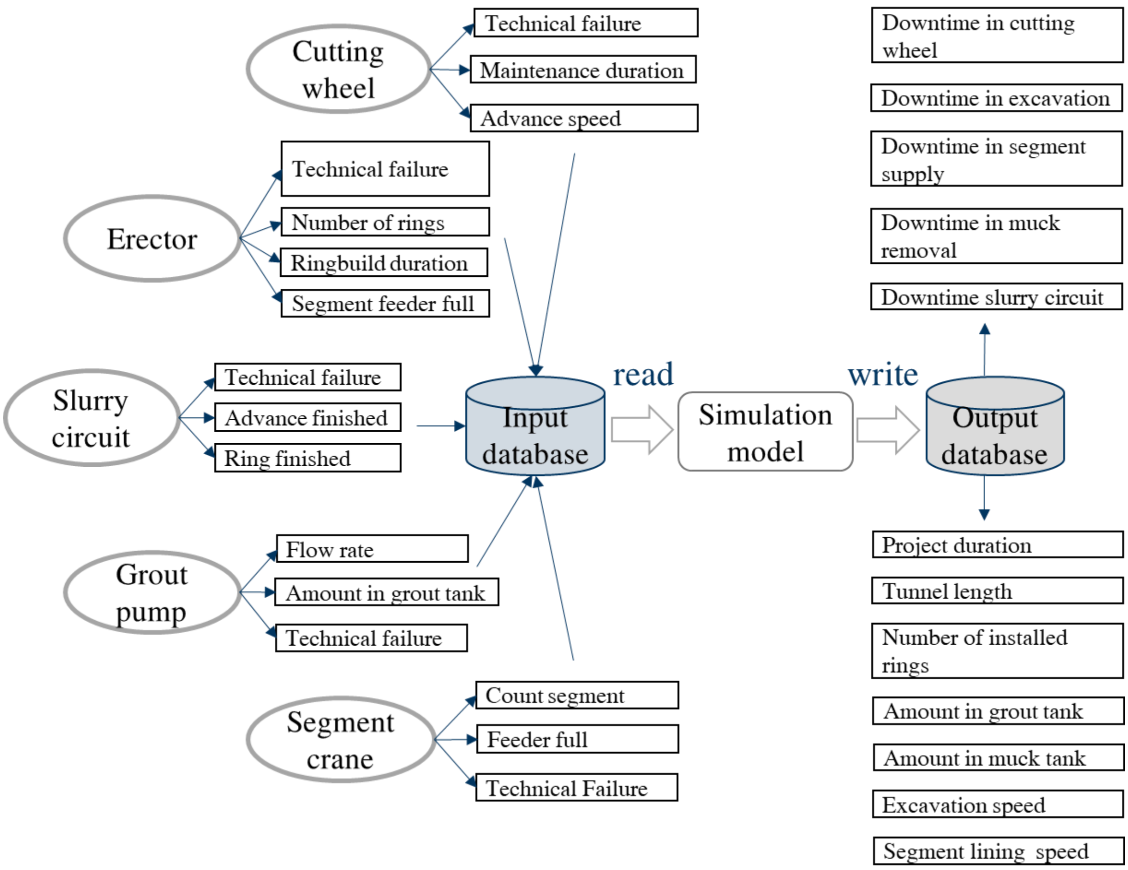


Fig. 4. Sample of the inputs and outputs connected to the simulation databases for the update phase

The simulation model will read the initial values at the beginning of the run. Nevertheless, the current values of the output variables are monitored during the simulation and will be stored in the output database file at the end of the simulation or at any desired stage of the project. The outputs of the simulation are mainly the duration of the project, the duration of the excavation and the duration of downtimes. In order to perform an actual target comparison in the course of the update, more data should be collected, such as the current status of the tanks, the current advancing speed, the current average process durations, the number of installed rings, and the current length of the tunnel.

These output values are compared with the real-time values at different stages of the simulation to detect any deviation. Accordingly, the input database can be updated with real-time data and the simulation can be executed again to get the updated results to predict the performance of the project for the next phase.

## 3.2 Integration of real-time data

The integration of real-time data can be tricky because of the non-deterministic nature of some variables. In the proposed TBM simulation model, different types of probability distribution functions (PDFs) are set in the planning phase to predict certain values. This could be, for example, the occurrence of technical failures in the system, the duration of failures and the advancing speed of the cutting wheel through different types of soils.

In the update phase, direct integration of deterministic input parameters in the model's input database will be performed. The current status of the processes should also be updated. In addition, the current length of the tunnel is updated to recalculate the paths of the transportation wagons inside the tunnel. To update non-deterministic data, a different approach will be used. Figure 5 shows the suggested concept to update the PDFs used to evaluate the probability of certain parameters offline (Brooks-Bartlett, 2018).

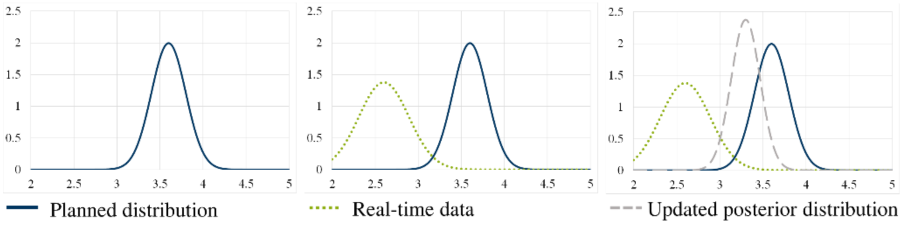


Fig. 5. Update approach for the probability distribution function

In this figure, the blue curve displays the PDF used in planning, which has been generated with a probabilistic approach using data from similar previous projects. During the execution of the project a new set of data, the real-time data, is now available. At a certain point in time, this data is gathered and analyzed to evaluate the validity of the proposed PDF. The green curve represents the probability function of the actual real-time data. Considering both sets of data, we can predict an updated posterior PDF (grey curve) that is more realistic and gives a better prediction of the project performance in the next phase of execution. This is one suggested way to consider real time data within the update without neglecting historical data, as historical data may still be relevant for the further prognosis of a project.

### 3.3 Modification of the offline simulation model

Figure 6 displays the main four steps to prepare offline simulation models for implementing an update. For the update phase, the initial values of the input/output parameters need to be dynamically changeable during the online-simulation.

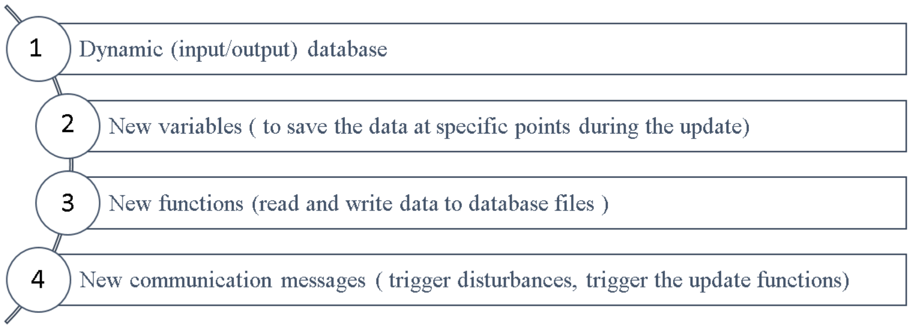


Fig. 6. The main steps to adjust the offline agent-based TBM model to implement real-time data

In the second step, new variables might be added to adjust the offline model in order to store the values of some variables dynamically during the execution of the simulation, which is needed for the evaluation of the current state in comparison with the real-time data. The third step is to create extra read/write functions to the model's agents to read/write inputs at different points during the execution of the simulation. The same concept is used to register the simulation outcomes before and after the update. The fourth step is to add the necessary communication messages between the agents to trigger the read/write functions at the desired stage of the simulation, or to trigger the unexpected disturbances that caused the deviation in the project's performance.

### 3.4 The validation of the implemented update concept

Validation tests are necessary to check the credibility of a model. The offline simulation model used in this research has been validated beforehand, so only an explicit validation of the update method itself is necessary. To ensure the validation of the simulation model, four tests have been conducted. One validation was conducted with a fixed value test. This validation will be shown exemplary in detail in this paper. Besides of this test, a test with fixed seeds (PDF), a test with various seeds and a test with Monte Carlo simulation has been conducted for the validation. These tests have shown that the simulation model is still valid after the implementation of the update method.

Figure 7 displays the basic steps of the validation concept developed for this study.

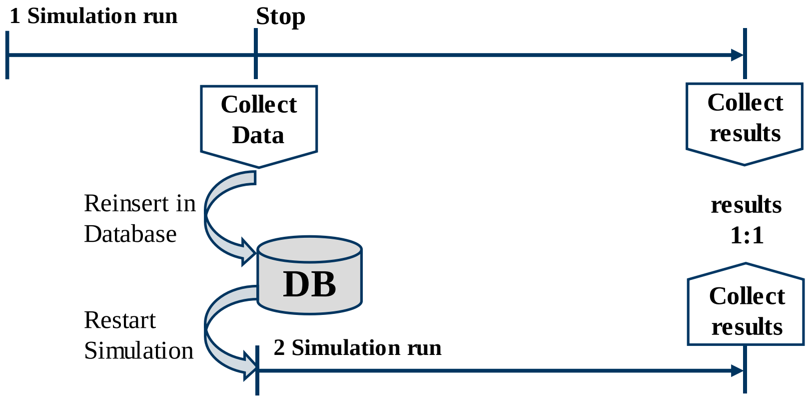


Fig. 7. The main concept of the validation test with fixed values

This validation concept is performed for the fixed value test. For this, the probability of various parameters in the simulation model is eliminated by setting the initial values of all variables to fixed values during the simulation run. The first run of the simulation from the initial point to the end gives the initial prediction of the project duration and performance. For the validation, the concept suggests to create synthetic validation data by stopping the simulation at one stage (for example after building 400 rings of the total 1000 rings) and then collect the output parameters at this point. Subsequently, the synthetic data is reinserted in the input database of the model and the updated simulation starts again from this new initial point to obtain the simulation results. Then, the results from the updated to the original simulation run are compared.

Therefore, the results shown in Table 1 must be hypothetically identical. A small deviation is detected though, due to the fact that some events in the model are controlled with timers during the simulation, which are restarted and then are causing time overlapping. Furthermore, some deviation is caused by the lack of tracking the moving parts as transportation vehicles, which is simplified in this model and which cannot be located during the simulation, resulting in the assumption to start from their initial position every time the simulation is executed.

Table 1. The results of the first validation test of the update concept

| | | Updated Simulation Model | Original Simulation Model | deviation |
|---|---|---|---|---|
| Project duration | [day] | 145.50 | 145.73 | -0.16% |
| Excavation advance | [hours] | 518.00 | 518.00 | 0.00% |
| Ring building | [hours] | 760.68 | 761.03 | -0.05% |
| Failure cutting wheel | [hours] | 51.67 | 51.67 | 0.00% |
| Technical failure grout pump | [hours] | 41.00 | 41.00 | 0.00% |
| Failure crane | [hours] | 0.50 | 0.50 | 0.00% |
| Maintenance erector | [hours] | 96.00 | 96.00 | 0.00% |

## 4 CASE STUDY

In this case study, the online-update method of the simulation model is tested as a planning and management tool during the execution of the project. Figure 8 illustrates the concept of the implementation taking the nondeterministic nature of the variables into consideration.

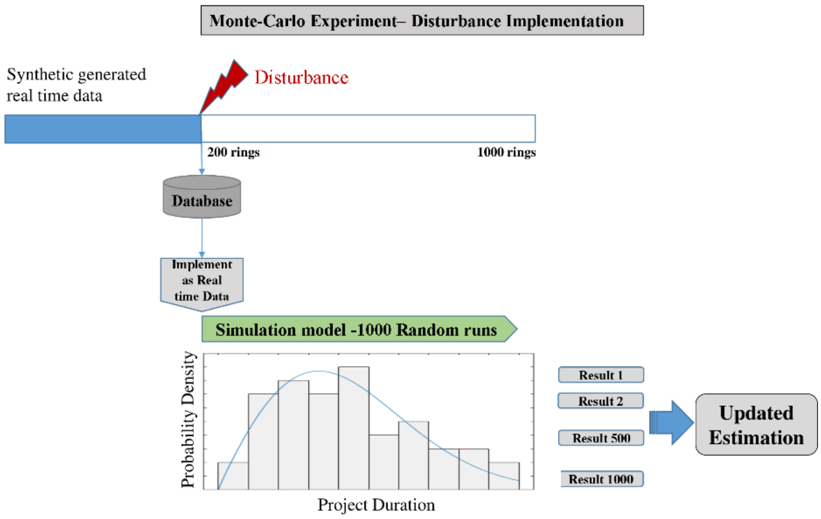


Fig. 8. Developed concept for the update of simulation models (case study)

In this case study, real time data is synthetically and exemplary generated. For the generation of the real time data, a simulation run is performed until the lining of 200 rings. At this stage, an unpredicted disturbance is simulated, which is assumed as a failure in the cutting wheel for 200 hours (i.e. 8.33 days). After the disturbance passes, the simulation output data is generated and used as the real time data. For the update of the projects performance, these real time data will be reinserted in the models' database as the initial value for the new run of the simulation. Due to the nondeterministic nature of the model, a Monte-Carlo experiment of 1000 runs will be performed from this point to the end of the project to get a new prediction of the project's duration and performance after the occurrence of this unplanned downtime of the cutting wheel.

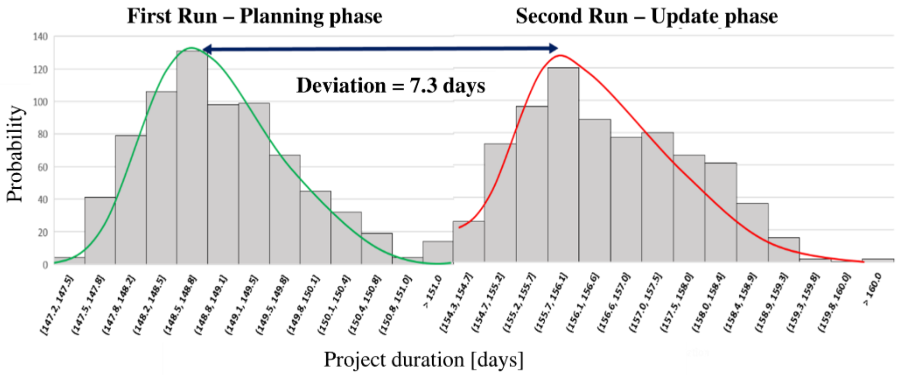


Fig. 9. Project Duration curves in the planning phase and update phase

Figure 9 shows the comparison between the initial results of the simulation in the planning phase and the results of the updated model after the occurrence of the extra failure during the execution of the project.

As shown, the most frequent prediction of the project duration in the initial case is 148.65 days, and for the updated simulation it is 155.9 days. The maximum predicted duration in the initial case is about 151 days. This value has increased to 160 after the disturbance. The deviation between the minimum and maximum value of the project duration in the initial case is about 4 days and it has increased to 6 days after the implementation of the disturbance.

Accordingly, an offset between the two curves can be noticed and it is rational regarding the implemented error. The 200 hours delay in the first phase of the excavation (i.e. 8.33 days) caused a total delay of 7.3 days in the total prediction of the project duration. This delay cannot exactly be the same at the end of the simulation because of the complex interaction between the agents (i.e. the processes in the real system). The malfunction of the cutting wheel for a certain time can affect the following processes. For example, it causes the erector to stop. Nevertheless, it may not affect the supply chain of the segments. Hence, the project duration is expected to be extended accordingly. However, during the maintenance of the cutting wheel, other preventive maintenance tasks can be executed and the delay in other tasks can be compensated. This is only a small example of the interaction that is analyzed in the simulation model. The real case can be more complicated, when more than one unplanned failure occurs, which might affect the project dramatically or has no significant effect at all. This analysis of the situation cannot be done without a proper online-simulation model.

## 5 Conclusion

Simulation models can be a useful managing and decision-making tool during the progress of a project. This can be achieved by developing online-simulation models that allow the adaption of real-time data at any stage of the project execution when the project's outcome starts to deviate from the predicted results. The integration of the real-time data in the simulation allows to obtain updated outcomes, which can help to take countermeasures when unplanned disturbances occur along the execution of the project. This paper proposed a method to turn an offline agent-based simulation model for TBM jobsite logistics into an online model to update the prediction of the project's duration and performance. In particular, if unplanned disturbances occur, this allows to evaluate the effect of these disturbances and to take suitable steps to optimize some processes or recover the downtime in the project's execution. This update is performed in four essential steps and validated afterwards. In the end, a practical example of the use of the online-simulation model is presented to explain the main purpose of the suggested concept.

In following research, it is planned to use this method to update simulation models with adapted non-deterministic data and to investigate their effects on the system.

## 6 ACKNOWLEDGMENTS

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# ANALYSIS OF WHOLE BUILDING LIFE CYCLE ENVIRONMENTAL IMPACT ASSESSMENT (EIA) TOOLS

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**Abstract:** Environmental impact assessment (EIA) tools are key mechanisms that link the environmental context of a project to the decision-making framework. Life cycle assessment (LCA) and green building rating systems (GBRS) are the two approaches commonly used to holistically analyze the environmental performance of the whole building. While GBRS are mostly based on a checklist with many qualitative criteria, LCA compels the practitioner to base the analyses in numerical evidence, which facilitates the comparison between design choices. Some rating systems, such as LEED, BREEAM and Green Star, have been incorporating LCA as one of their criteria. This practice tends to increase in criteria-based tools, because of the market and governmental claims for better awareness of the construction industry ecological impacts. Therefore, the goal of this article is to discuss both whole building life cycle EIA tools, life cycle assessment (LCA) and green building rating system (GBRS), comparing their methodological concepts as well as the effort of combining both approaches. It was noticed that although there are many differences between EIA tools, the combination of both approaches would bring substantial benefits in identifying and mitigating the potential environmental impacts of buildings. Therefore, further research is needed to create a design process framework that unifies GBRS and LCA methodologies, providing a more comprehensive overview of a building's environmental impacts.

**Keywords:** Environment impact assessment (EIA), Life cycle assessment (LCA), Green building rating system (GBRS).

## 1 INTRODUCTION

The building industry brings substantial benefits to the world's society and economy, and it is a key element for sustainable development. But such benefits come with great environment impacts. It is estimated that 40% of the global greenhouse gas (GHG) emissions derives from the building sector, including the production of building materials and direct and indirect energy consumption (WBCSD, 2018). But such high environmental cost also comes with a great potential to shift this scenario, and buildings have become a target when it comes to GHG emissions reduction initiatives.

Environmental impact assessment (EIA) tools are developed to allow decision-makers to understand the impacts of their choices by connecting the environmental context to the decision-making framework (IEA, 2005). EIA tools can be divided into 3 main groups:

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(1) Energy and ventilation modelling;
(2) Life cycle assessment (LCA) tools;
(3) Passive tools, such as green building rating systems (GBRS), guidelines or checklists and Environmental Product Declarations (EPD)

Many studies of building impact assessment limited their analysis to the energy performance during the usage stage. But, especially with the advance of nearly zero energy building (NZEB), when the new technologies allow buildings to decrease energy usage and apply cleaner off-grid sources, embodied energy impacts derived from materials became a greater issue. Although operational energy still represents the greatest part on the building's life cycle, NZEB may lead to buildings with a higher portion of embodied energy and embodied carbon (Sartori and Hestnes, 2007). Therefore, in order to holistically analyze the performance of the whole building throughout its life cycle, LCA and passive tools from the above classification are used. In terms of passive tools, this article will focus on green building rating systems (GBRS) because it is the most commercially used whole building life cycle passive tool (Ade and Rehm, 2020).

Therefore, the goal of this article is to discuss the two types of whole building life cycle EIA tools, life cycle assessment (LCA) and green building rating system (GBRS), comparing their methodological concepts as well as the effort of combining both approaches.

# 2 Methodological differences between LCA and GBRS

## 2.1 Life cycle assessment (LCA) of buildings

The main goal of LCA is to address the potential environmental impacts of all inputs and output flows within a product's life cycle, from raw material acquisition, manufacture, use, maintenance, until end-of-life (Standard, 2006). Figure 1 shows the four phases with-in the methodology (Standard, 2006): goal and scope definition, inventory analysis, impact assessment, interpretation.

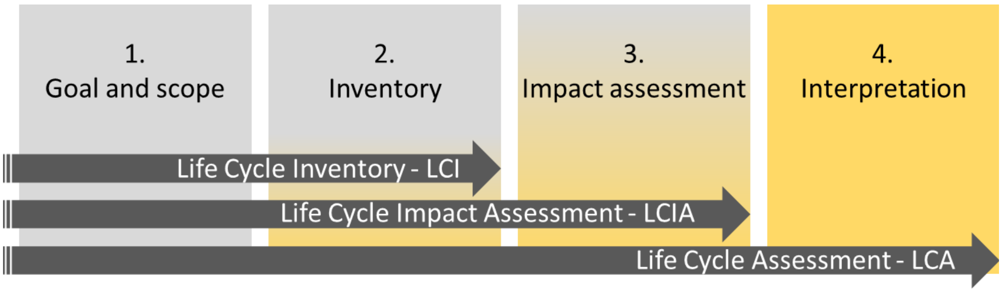


Figure 1: LCA phases

Studies that applied LCA methodology for buildings started in the '90s, and it has been growing ever since (Buyle et al., 2013), especially after the release of relevant standards (Standard, 2011). The British standard supports the decision making and documentation process and establishes the concepts to be followed by all practitioners, e.g. system boundaries, function units and reference study period. No regulation dictates the use of LCA methodology for the assessment of the impacts of construction-related activities (Larsson and Trusty 2004; Pomponi and Moncaster, 2018).

Because of the increasing interest of governmental groups in impacts of construction industry, LCA has become more attractive, particularly for materials manufacturers, through publication of environmental product declarations (EPD). EPDs communicate the environmental information of construction products, services and processes by quantification based on scientific data of all the input and output flows (Standard, 2014). In other words, EPD is a document owned by manufacturers that publicly dis-closures the LCA of their products. Although EPDs do not guarantee a more sustainable construction material, the understanding of the chemical emissions can diminish the impacts on the environment by motivating changes in the manufacture processes. Likewise, it gives the design decision-makers more understanding of their material choices, since EPDs allow them to make quantitative and scientific-based comparisons.

Although the publication of the standard represented a progress toward LCA of buildings, it is still difficult to compare the results of different assessments. The reasons include the geographical location of the building, which defines the weather, materials production chains, regional electricity mix, local regulations, in addition to technological, cultural and social differences (Buyle et al., 2013; Islam et al., 2015; Ortiz-Rodríguez et al., 2010). The significant variability of results found in many LCA studies (Pomponi and Moncaster, 2018; Dixit et al., 2010), indicates that there is still significant opportunity for more transparent and systematic assessments.

## 2.2 2.2 Green building rating system

GBRS are voluntary labelling schemes that measure the performance of green buildings by assigning credits and weights to environmental factors, sorted into different categories. The conception of GBRS was motivated by Green Building Councils (GBCs) around the world, aiming to communicate to the market the extent of a building's commitment to sustainable development (Ade and Rehm, 2020). Therefore, owners or developers voluntarily submit their building through a third part evaluation process to validate the green strategies applied. The result of this evaluation is often used by the building industry as a marketing strategy (Ade and Rehm, 2020).

Table 1 shows information about 6 different rating systems: Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Green Star (GS), Haute Qualité Environnemen-tale (HQE), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), and Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB). These rating systems, besides being well known worldwide, are on the top list of the most cited in Scopus database (Bernardi et al., 2017; Li et al., 2017).

Energy, water and material are the most common categories analysed by rating systems, followed by site and indoor and outdoor environment quality. Energy is the category that has the greater weighting in most GBRS worldwide, accounting for 25% - 30% of the total credits available (Illankoon et al., 2017; Mattoni et al., 2018; Shan and Hwang, 2018; He et al., 2018). LEED is one of the most energy-oriented systems, focused on the reduction of energy demand during operational stage by applying renewable energy sources and reducing cooling and heating loads (He et al., 2018). The concentration of credits in only one category might become an issue if a project achieves a certain certification level without any credits in another critical category, such as indoor environment quality (Wu et al., 2016).

Based on the main pillars of sustainability, rating systems mainly look at the environmental impacts (Doan et al., 2017), with reduced emphasis on analysing economic, social and institutional issues. Other aspects that need more attention in rating systems are prevention from environmental disasters, Life Cycle Assessment, reuse and retrofit (Mattoni et al., 2018). Since there isn't a common framework followed by all rating systems, studies show inconsistency on the results when analysing the same building with different certification process (Wallhagen and Glaumann, 2011). This is also true when comparing the performance of buildings located in different countries certified by the same rating system (Wu et al., 2016).

Table 1: Most cited GBRS

| | LEED | BREEAM | Green Star | HQE | CASBEE | DGNB |
|---|---|---|---|---|---|---|
| Country | International | International | Australia | International | Japan | International |
| Certification body | US Green Building Council | Building Research Establishment group | Green Building Council of Australia | Cerway - France | Institute for Building Environment and Energy Conservation (IBEC) | German Sustainable Building Council |
| First version | 1998 | 1990 | 2002 | 1997 | 2004 | 2008 |
| Latest update | 2019 | 2016 | 2017 | 2016 | 2014 | 2018 |
| Applicability | 167 countries | 83 countries | 1 country | 16 countries | 1 country | 20 countries |

## 2.3 Comparison analysis

Regarding the methodological approach, one similarity between LCA and GBRS is the effect of human judgment when setting up the importance of each impact category. In rating systems, this decision is based on the category weighting, while in LCA this decision is made during the interpretation process. This human factor gives both assessments types a level of subjectivity, not based on scientific facts but on the developer or practitioner's value judgments (Ade and Rehm, 2020).

There are also many differences between both assessment tools. Criteria-based systems such as GBRS are more flexible in terms of which category a building is more likely to obtain credits. In other words, if a building does not perform so well in one category, it can be compensated by a higher performance in a different criterion. On the other hand, LCA calculates the impacts through the entire building life cycle, providing numerical evidence when comparing design choices (Mattoni et al., 2018). Another important difference relies on the way the outputs are informed. While in rating systems the results emphasize the improvements and advantages of the design decisions by providing a sustainability level, LCA outputs are focused on the environmental damage, such as natural resources depletion. This difference makes rating systems so appealing to the construction industry and allows green certifications to be used as a marketing strategy.

Although LCA calculates a building's environmental impact systematically and holistically, the analysis is made focused in a global or regional spectrum and the pros and cons of a new building in a community and neighbourhood context are of-ten ignored (Buyle et al., 2013). Specific local ecology and infrastructure impacts, such as the influence of the building on the micro-climate, wind and solar access, as well as the ability to modify the surrounding transportation system, isn't addressed with an LCA approach (IEA, 2005). Also, multi-criteria systems can inform a wider set of LCA impact categories (Collinge et al., 2015). Therefore, a more comprehensive environmental impact assessment tool would incorporate both measure-based methods, such as LCA and energy modelling, with qualitative criteria-based schemes (IEA, 2005; Buyle et al., 2013; Collinge et al., 2015).

## 3 GBRS INTEGRATING LCA

Following the construction industry transparency demand, Green Building Rating Systems (GBRSs) have also been incorporating Life Cycle Assessment (LCA) into their credits system. By introducing LCA as one of the criteria, rating systems in-crease the credits given to simulation of buildings performance, founding the assessment on empirical calculation methods. Such practice tends to increase in criteria-based tools, because of the market and governmental claim for a better awareness of the construction industry ecological burdens (Forsberg and von Malmborg, 2004). Apart from the well-known check-lists practices, LCA compels GBRS practitioners to search for more authentic sustainable solutions, stimulating the search for innovations in the design. Yet, a robust and systematic LCA approach becomes a challenge when applied in a user-friendly framework such as criteria-based systems. Table 2 shows the LCA requirements for 6 different rating systems.

Since there are many types of certifications available, such as housing, interior design and in-use, this study focuses on the certification of new construction non-residential buildings, because that is the type of certification that encompasses a more diverse kind of buildings. Also, when available, the international version was chosen.

Among the main methodologies used by regulations and rating systems to address embodied impacts, the ones mostly used by GBRS are reporting, comparison and rating (Bionova, 2018). Considering the rating systems analyzed in this study, BREEAM is the only one that calculates the impacts construction projects with the aim of reporting it. The intention of BRE Global is to collect enough data to create a benchmark robust enough to be included on the future BREEAM updates (Establishment, 2016). The comparison methodology confronts the impacts of a design baseline with an environmentally improved proposed design. In this case, in order to get the desired results, the impacts of green decisions should also be acknowledged (Bionova, 2018). The baseline design is self-declared in LEED and "must be of comparable size, function, orientation, and operating energy performance" (USGBC, 2013). In Green Star the reference building is also self-declared but can also be a hypothetical building representing standard construction practices or an actual building constructed in the last five years similar to the proposed building (Australia, 2017). DGNB uses the rating methodology when LCA results are confronted with limit, target and reference values (DGNB, 2018). These reference values are self-proclaimed based on different types of buildings previously certified. Although it is a good start point to create benchmarks, it does not represent the entire construction industry practices, because it only considers buildings that were certified (Schlegl et al., 2019).

Table 2: Life cycle assessment requirements based on green building rating system

| | LEED v4.1 BC+D New construction | BREEAM International New Constructions 2016 - Non-residential fully fitted | Green Star - Design & As Built v1.2 | HQE - Nonresidential building under construction | CASBEE for buildings (new construction) | DGNB - New construction buildings - commercial building |
|---|---|---|---|---|---|---|
| Weight | 4.5% | 5.9% | 6.40% | 3,1% | 31.60% | 9.50% |
| Part of the building assessed | Structure and enclosure | _Mandatory: Envelope, structure, finishes, upper floors, internal walls, _Extra credits: Foundations, internal finishes, building services and landscaping. | - | _Structure or finishing _Structure and finishing | _Structure | _Structure - construction works:. _Structure - services: |
| Characterization model (1) | TRACI, CML and ReCiPe | - | IPCC, WMO, CML | - | _ | CML |
| Building service life cycle (years) | at least 60 years | 60 | 60 (suggested) | - | 60 | 50 |
| Method | Reporting or comparison | Reporting | Comparison | Comparison | Comparison | Reporting or rating |
| Recognized Software tool | ATHENA Impact Estimator, Envest 2, LCA Design SimaPro, GaBi | ByggLCA, Conpact, OneClickLCA, eTool, Green Guide, COCON, ELODIE, MRPI Freetool MPG, nova EQUER, SBS Building Sustainability, Anavitor/ECO2. | _ | ELODIE, Team Building | Internally developed spreadsheet | _ |
| System boundary | Cradle - grave | _Flexible | Flexible | - | Cradle - grave | Cradle - grave |
| Functional unit (2) | ft2 | - | m2 GFA | - | Kg CO2/yr.m2 | m2 SA*a |
| Credits for EPDs | 1 | 1 | Up to 3 | Up to 7 | - | - |

(1)TRACI (Bare et al., 2012); CML(University, 2019); ReCiPe (Goedkoop et al., 2013); IPCC (UNFCCC, 2019), WMO (Organization, 2020); (2) Gross floor area (GFA); suface area multiplied by the reference year considered (m2 SA*a)

- **Leadership in Energy and Environmental Design (LEED)**

The latest update of LEED for new building design and construction, launched in November 2013, gives up to 5 points for building's life cycle impacts reduction, which represents 4.5% of all credits available (USGBC, 2013). It is possible to get these credits by renovating part of the building, reusing some materials or preforming an LCA of the structure and enclosure of the building. For the latter option, the assessment compares the final solution with a baseline building similar to the proposed design, demonstrating a minimum 10% reduction on the impact categories (USGBC, 2019). LEED's reference guide establishes some of the scope elements, such as a 60 years service life and a cradle to crave system boundary. It also indicates the appropriate impact assessment methods for North American projects and global characterization models that should be used in other parts of the word (USGBC, 2013).

- **Building Research Establishment Environmental Assessment Method (BREEAM)**

On the latest international version of BREEAM for new non-residential fully fitted buildings, there are up to 6 points when performing a whole-building LCA, which represents 5.9% of all credits available. BREEAM recognizes that LCA is a methodology that still needs to mature. Thereby, the credits available focus mostly on the robustness of the software tool, method, data and scope of the assessment, aiming to create benchmarks by collecting many building performance information (Establishment, 2016). The credits for performing an LCA is based on the quality of the assessment method and data, as well as on the scope of building elements included in the analyses (Establishment, 2016).

- **Green Star (GS)**

Green Star follows the same comparison methodology as LEED, in other words, the assessment results can be compared with a similar usage, construction and operation building, or with a hypothetical building that represents the contemporary standard practices (Australia, 2017). It is unclear what part of the building the practitioner should consider, and it is flexible on the system boundary, which may lead to a broad and unreliable results. But Green Star establishes that the performance should be peer-reviewed and carried out by a verified experienced LCA practitioner. There are up to 7 points available for LCA that represents 6.4% of all credits available. The credits earned depend on the cumulative percentage impact reduction of 7 mandatory impact categories (Australia, 2017), but more points are available for additional life cycle impact report impacts.

- **Haute Qualité Environnementale (HQE)**

From the rating systems analyzed in this report, HQE is the only one that does not clearly implement LCA (Ismaeel, 2018). Although the practical guide for non-residential building under construction considers LCA as one of the methods to limit the environmental impact of the building, it does not specify the basic technical criteria, such as the impact categories and the system boundaries (Cerway, 2014). The assessment is made to create awareness of the environmental impacts caused by the chosen construction materials, and not to demonstrate a real reduction on the burdens. This lack of clear requirements may lead to misunderstandings and confusion, discouraging the practitioner to include this assessment as one of the certification criteria.

- **Comprehensive Assessment System for Built Environment Efficiency (CASBEE)**

The only impact category analyzed by CASBEE is the greenhouse gas emissions (Life Cycle CO2 – LCCO2). There are two ways of conducting a LCCO2. The first one is through standard calculation using references values of a level-3 performance building, and the other way is using individual calculation with a highly accurate LCCO2 estimative (IBEC, 2014). Using the first method, the CO2 emissions results are carried out automatically as the carbon-related criteria are filled out in a spreadsheet developed by CASBEE. In other words, the life cycle approach is not a criterion option because the carbon emissions levels are calculated along with the certification process. The cradle to grave approach estimates the embodied carbon of the main structural materials and uses CO2 emission coefficient to estimate the primary energy consumed during operation. The categories associated with LCCO2 are within Q2 – Quality of service, LR1 – Energy and LR2 – Resources & materials, whose sum of points represents 31.6% of all certification credits. According to N. Lee, Tae, Gong, and Roh (Lee et al., 2017), CASBEE methodology is not able to investigate the benefits of green materials usage, due to its limited database that only brings major construction materials, namely, concrete, steel and wood.

- **Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)**

From all rating systems analyzed, DGNB has the most detailed description and specifications for the life cycle assessment category. One of the reasons is that the rating system focus on holistic approach, emphasizing the buildings performance through LCA (DGNB, 2019). The certification system provides reference values for most of the impact categories, based on a top-down statistical study conducted in 2017 gathering data from approximately 200 buildings (DGNB, 2018; Schlegl et al., 2019). It also establishes limit and target factor applied to the reference values. Points are awarded if the LCA results comply with the reference values, but highest points are earned if the impacts reach or fall below the target values. Additional points are awarded for buildings that focus on carbon-neutral in operation and construction, according to the agenda 2030 (Architecture2030, 2019). It is likely that this requirement will gradually become part of the certification in the upcoming versions (Braune et al., 2018).

# 4 DISCUSSION

The combination of different impact assessment methodologies, such as LCA and GBRS, is a holistic way to address the building's ecological burdens throughout its life cycle. But the existent tools still struggle to deliver an assessment framework that combines both approaches, especially during building's design process. Although there is an effort of some rating systems to increase the awareness of construction materials impacts, this is still an optional criterion. Perhaps, building's LCA methodology is still a long and extensive process for designers and building consultants, and the lack of a strong database to support benchmarks and reference values might discourage green building councils to better establish LCA as a certification pre-requisite.

As indicated above, CASBEE and DGNB are the ones among the rating systems analyzed that mandatorily considers LCA. These are also the rating systems that mandatorily considers the impacts from the energy demand during use, such as appliances, HVAC and lighting. For all the other rating systems analyzed, even when a cradle-grave approach is stated, they do not necessarily include the energy required for operational energy use, but only maintenance, material replacement and refurbishment. In fact, some rating systems give extra credits when including operational energy, such as Green Star and BREEAM. It is important to notice that the energy efficiency of the building also depends on the thermal and physical properties of the envelope's assembly. In other words, the choice of envelope material is strictly related to the building's energy efficiency during operation (Najjar et al., 2019). It is possible that an apparently non-environment friendly material provides the building with a great energy operational performance, but this analysis can only be made with a systematic LCA approach.

GBRS assessment considers quantitative (measure-based) and qualitative (feature-specific) criteria. Quantitative criterion is based on the building's performance supported by scientific techniques and can be more complicated to implement because it depends on specific calculation methods and simulations. Nevertheless, increasing quantitative measures in GBRS can increase the scientific value behind the credits (Collinge et al., 2015), while motivating innovation in the design (He et al., 2018). On the other hand, qualitative criterion points are granted whether a certain environmental issue is applied or not (He et al., 2018), which makes this type of credits simpler to assess. However, there are some drawbacks. He et al. (2018) pointed out that qualitative credits can be used as checklists by practitioners, limiting building design by indicating commonly used green techniques. Besides, it is more complicated to acknowledge the actual building performance only by choosing and applying different strategies.

Future research is needed in order to formulate a framework that considers both EIA tools approaches during the design process, so decision-makers are able to identify and reduce the building's impact on the environment.

## 5 Conclusion

This article analyzed two different whole building environmental impact assessment (EIA) tools, named life cycle assessment (LCA) and green building rating system (GBRS). The authors discussed their main characteristics, pointing out their disparities and similarities. Although there are many differences between the EIA tools mentioned, the combination of both approaches would bring substantial benefits in identifying and mitigating the building's potential environmental burdens.

All rating systems analyzed in this article include LCA in their certification scheme. Therefore, this article also discussed some of the rating system requirements for the LCA criterion, such as building's life service, functional unit and em-bodied emissions methodology. It was noticed that the awareness of embodied emissions tends to increase in rating systems, and the lack of a robust database to support benchmarks might discourage further developments.

In sum, further research is needed to create a design process framework that includes GBRS and LCA methodologies, providing a more comprehensive overview of the building's environmental impacts.

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# IMPACT OF SYSTEMIC HETEROGENEITY ON THE FAILURE PROPAGATION OF NETWORKED CRITICAL INFRASTRUCTURE SYSTEMS: AN EXPLORATIVE STUDY CONSIDERING THE HETEROGENEITY IN SUSCEPTIBILITY TO OVERLOAD FAILURE

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**Abstract:** Modern CISs are becoming increasingly topologically interconnected and functionally interdependent. As a result, failure in one system may cause dependent components in other systems to fail, triggering cascading failures in networked CISs. Different CISs are heterogeneous in a variety of aspects, such as their topological characteristics and disaster resistance capacities. For instance, power grids are more susceptible than water supply systems to overload failure due to flow redistribution under disaster. Such systemic heterogeneity may significantly influence the failure propagation process across different CISs. However, despite the increasing volume of literature that examines failure propagation risks in networked CISs, few studies have accounted for systemic heterogeneity and its potential effects on cascading failures. The aim of this study is to assess the significance of such effects using one typical heterogeneity factor between the power and water supply systems. Firstly, a representative modeling approach of failure propagation, namely artificial flow based (AFB) approach, is selected through a thorough literature review. Secondly, two different artificial flow models (AFM) are developed using the AFB approach. Both models represent two interdependent, district-scale power and water systems, and they are distinguished by whether the systemic heterogeneity in susceptibility to overload damage is modeled by proper parameter settings. Lastly, both models are subjected to a simulated earthquake scenario, and three metrics are proposed to assess the overall responses of the two systems. The results from the two models are compared, which reveals that the magnitude of disaster impact of CISs would be notably overestimated when the systemic heterogeneity is not taken into consideration. The practical implications of the results are also discussed in the paper.

**Keywords:** Systemic Heterogeneity, Failure Propagation, Networked Critical Infrastructure Systems, Disaster Impact.

## 1 INTRODUCTION

Critical infrastructure systems (CISs), such as power and water supply systems, play a significant role in our daily life (Wang et al., 2013). Modern CISs are becoming more and

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more networked and dependent on each other for proper functioning (Buldyrev et al., 2010). This has resulted in many bi- or multi-directional dependences, also referred to as interdependencies, between different CISs. Due to the presence of these interdependencies between CISs, the failure of a component in one system may cause failure of components in another system (Zhang et al., 2018). As a result, local failure may unpredictably propagate throughout the entire system-of-systems and could result in global failure.

Systemic heterogeneity of interdependent CISs refers to the differences between the CISs in terms of their physical network features, transported material properties, operational characteristics and responses to disaster (De et al., 2008; Wang et al., 2019). Systemic heterogeneity is the main cause of difference in failure propagation mechanisms among different CISs (Duenas-Osorio et al., 2007). A typical example of systemic heterogeneity factor is the heterogeneity in system susceptibility to overload failure. For instance, when disasters happen, compared to the water supply system, the power grid is more susceptible to component overload failure due to power flow redistribution (Zuloaga et al., 2019). Overload failure is easier to avoid in the water supply system because proper technical or managerial measures can be taken in a timely manner to prevent the amplification of damage in the network. That being said, the impact of systemic heterogeneity on failure propagation across CISs has not been adequately recognized and addressed in prior research. While several studies have pointed out the possible impact of systemic heterogeneity and the need to account for this impact in the modeling of CISs failure propagation and the estimation of CISs disaster losses (De et al., 2008), the extent of this impact and its mechanism have largely remained unknown. CISs are largely considered homogenous in these models with respect to their disaster response patterns, which inevitably leads to significant inaccuracies in the simulated failure propagation processes and estimated overall disaster impacts (Duan et al., 2020).

In this study, one typical systemic heterogeneity factor, namely heterogeneity in system susceptibility to overload failure, is examined based on a case study. The impact of this factor on the failure propagation of an interdependent CISs network, which is comprised of a water supply system and a power supply system and represented using a widely adopted CISs modeling approach (i.e. artificial flow-based (AFB) network modeling), is assessed and analyzed. Results from this study are expected to raise the awareness of drawbacks in current CISs failure propagation models, and serve as a foundation for the development of more reliable failure propagation modeling approaches in future research.

# 2 Related Work

## 2.1 Network-based Modeling of Interdependent CISs

Interdependent CISs are easily modeled using network-based approaches with nodes and links representing system components and their connections respectively. Hence, with the progress made in network science over the years, it has become easier to model interdependent CISs (Ouyang, 2014).

The network-based modeling approaches can be classified under two main categories. In the first category, only the topology of the network is modeled. This approach is known as the topology-based (TB) approach. A typical model based on the TB approach is the percolation model (Buldyrev et al., 2010). In the second category, both the network topology and material flow across system components are modeled. The main approach under this category is the network flow-based approach (Ouyang, 2014). The typical models based on the flow-based approach are AFB network model (Wu et al., 2016) and real flow-based (RFB) network model (Ouyang et al., 2009), which are differentiated based on whether the model settings adopt real flow attributes of CISs or their proxy parameters and indices. Typical indices used to represent system flow in AFB models include betweeness (Wu et al., 2016) and path number (Wang et al., 2018). RFB models use real flow indices such as water flow rate and current flow rate to analyze the operation characteristics of systems. A few other network models have also been proposed in prior research, that integrate other logical algorithms to describe interactions between network components. Examples include the petri-net (PN) (Ouyang et al., 2009) and Bayesian network (BN) models (Wang et al., 2018).

## 2.2 Simulation of Failure Propagation Across Networked CISs

Researchers proposed a few TB approaches to model the mechanism of failure propagation through CISs networks. One common insight of these approaches is that failure of a node would lead to the failure of all edges connected to the node, and vice versa (Buldyrev et al., 2010). Failure will stop propagating when all nodes within a spanning cluster remain functional under the disaster simulation. Network flow-based approaches are used to model the functionality of CISs. However, since it is difficult to precisely model the flow within the CIS (Chowdhury and Zhu, 2019), some flow indices were introduced. This has led to the development of two variants of the network flow approach, namely AFB network model (Johansson and Hassel, 2010) and RFB network model (Ouyang et al., 2009). The failure propagation process of network flow-based approach can be summarized as a redistribution of flow within a system when a node fails. Consequently, some other nodes may suffer overload damage if their capacity is exceeding. This process is repeated iteratively until the actual load at every remaining node in the network is no larger than its capacity.

Other models, such as agent-based model (ABM), system dynamics (SD) model and input-output model (IOM), have also been adopted to model failure propagation of CIS-related systems. However, most of these studies focused on the interactions between different CISs, or between CISs and economic system or social systems (Thompson et al., 2019; Bagheri et al., 2007; Rai and Henry, 2016), while paying little attention to modeling failure propagation across interdependent CISs.

Four criteria, namely effectiveness, complexity, maturity, and replicability, are used to compare the existing approaches for modeling failure propagation across CISs. Effectiveness refers to the ability of the modeling approach to accurately model failure propagation (Duan et al., 2020); Complexity mainly refers to computational complexity in modeling the failure propagation (Ouyang, 2014; Duan et al., 2020); Maturity refers to the development level of each approach, which can be measured by the number of existing publications and applications (Ouyang, 2014; Duan et al., 2020); Replicability describes the difficulty in replicating an approach based on the descriptions available in relevant prior publications and accessing relevant empirical data (Ouyang, 2014). The effectiveness, complexity, maturity and replicability of each modeling approach are assessed and rated “L” (low), “M” (medium) or “H” (high) based on the rating criteria proposed in prior research (Ouyang, 2014; Duan et al., 2020). The assessment results are summarized in Table 1.

Although a bulk of research has been conducted to advance the understanding of the mechanism of failure propagation across CISs, however, the impact of system heterogeneity on this mechanism is still a relatively unexplored topic. Failure to consider systemic heterogeneity when modeling interdependent CISs would result in inaccuracies in the simulated disaster response behaviors of the systems. This paper therefore aims to reveal and assess the importance of systemic heterogeneity when modeling failure propagation across interdependent CISs.

Table 1: Assessment of approaches for modeling failure propagation across CISs.

| Approach | Criteria | | | |
|---|---|---|---|---|
| | Effectiveness | Complexity | Maturity | Replicability |
| TB | L | L | H | H |
| AFB | M | M | H | H |
| RFB | H | H | M | L |

## 3 Methodology

In this study, one typical heterogeneity factor existing between the power and water supply systems, namely heterogeneity in system susceptibility to overload failure, is examined for its impact on failure propagation in an interdependent CISs network comprised of the above two systems. Firstly, a baseline model is built, using a typical and easily replicable modeling approach, to simulate the failure propagation in the CISs. Secondly, a modified version of the baseline model is built, by taking into consideration the systemic heterogeneity factor. Lastly, three impact metrics are introduced to compare the failure propagation process and outcomes obtained from both models when they are subjected to a simulated disaster. The above methodology is further explained below.

### 3.1 Baseline Model

The approach for modeling the baseline model is selected based on the four criteria described in Section 2.2. Specifically, in the best case the selected approach should be of high effectiveness, low complexity, high maturity and high replicability. The ratings of the AFB approach in the four criteria are the closest to the best case among all existing approaches, with medium effectiveness, medium complexity, high maturity and high replicability as can be observed in Table 1. Therefore, the AFB approach is selected for this study. The modeling of CISs using the AFB approach is described in detail below.

The networked power-water supply system can be denoted as $S = \{S_p, S_w\}$, where $S_p = (V_p, E_p)$ and $S_w = (V_w, E_w)$. The element $V_p(V_w)$ represents the system nodes and $E_p(E_w)$ represents the system links. The flow relationship $R^{ik}$ between nodes $i$ and $k$ in each CIS can be expressed as follows:

$$R^{ik} = \begin{cases} 1 & if\ there\ is\ flow\ from\ node\ i\ to\ node\ k \\ 0 & if\ there\ is\ no\ flow\ from\ node\ i\ to\ node\ k \end{cases} \tag{1}$$

The interdependencies between power and water supply systems can be described as unidirectional dependency links between them. Interdependency $I_{ij}$ between node $i$ in $S_p$ and node $j$ in $S_w$ can be expressed as follows:

$$I_{ij} = \begin{cases} 1 & if\ node\ i\ (i \in V_p)\ is\ dependent\ on\ node\ j\ \ (j \in V_w) \\ 0 & if\ there\ is\ no\ relationship\ between\ node\ i\ (i \in V_p)\ and\ node\ j\ (j \in V_w) \\ -1 & if\ node\ j\ \ (j \in V_w)\ is\ dependent\ on\ node\ \ i\ (i \in V_p) \end{cases} \tag{2}$$

Betweenness is a widely used index to represent the flow within a system (Wu et al., 2016). The betweenness of node $t$, denoted as $BV(t)$, which is defined as:

$$BV(t) = \sum_{i\neq k, i\neq t, k\neq t} \frac{g_{ik}^{t}}{g_{ik}} \quad (3)$$

where $g_{ik}$ denotes the number of shortest paths starting from node $i$ and ending at node $k$, and $g_{ik}^{t}$ denotes the number of shortest paths from node $i$ to node $k$ and passing through node $t$.

The load of node t, denoted as $LV(t)$, can be represented by its betweenness value $BV(t)$ (Wu et al., 2016). At the same time, the capacity of node $t$, denoted as $CV(t)$, is assumed to be proportional to the initial load $BV_0(t)$ (Wu et al., 2016):

$$CV(t) = (1 + \beta) \cdot BV_0(t) \quad (4)$$

The model setting of the baseline model, which includes all the parameters constituting Eq (1)-(4), is designed based on descriptions reported in prior research (Chowdhury and Zhu, 2019). Failure propagation can be modeled as follows: if actual load $BV(t)$ of node t exceeds its capacity $CV(t)$, the node will experience overload damage. Overload damage is possible in both CISs. Failed nodes are automatically removed from the network and the betweenness value of every remaining node in the redistributed network is recalculated and updated. The above process is repeated iteratively until the actual load at every remaining node in the network is no larger than its capacity. Links are not subject to failure. The tolerance parameter in Eq (4) is set to be 0.02 based on China standard (2009).

## 3.2 Modified Model

As the second step of the methodology, the baseline model is modified to consider the systemic heterogeneity factor selected in this study. The heterogeneity factor proposes that overload damage would not occur to components in the water supply system. This proposition is explained by the way components in both systems are designed. In power grids each component has a flow capacity that cannot be exceeded or else the component would be damaged almost instantly. Power flow redistribution under disaster may cause the actual flow through certain components to exceed their capacity and hence cause overload damage of the components. However, in water supply systems, flow rates are continually adjusted by the pump stations and in case of any disruptions, timely measures can be taken to avoid overload damage of components.

To incorporate this heterogeneity factor in failure propagation simulation, the capacity $CV(t)$ of node t should always be larger than its actual load $BV(t)$. Hence, Eq (4) is modified to be:

$$CV(t) = \begin{cases} (1 + \beta(p)).BV_0(t) & if\ t \in V_p \\ (1 + \beta(w)).BV_0(t) & if\ t \in V_w \end{cases} \quad (5)$$

where $\beta(p)$ and $\beta(w)$ are the tolerance parameters of power and water supply system, respectively. In this modified model, $\beta(w)$ is set at a large value of 10. This value is determined after several test simulations, and is chosen to ensure that for every node in the network its actual artificial flow never exceeds its capacity, such that no overload damage would occur. All other parameters in the modified model are same as in the baseline model.

## 3.3 Impacts Metrics

Three metrics, namely impact on failure scale (Wu et al., 2016), propagation time (Mao and Li, 2018), and failure order (Chang et al., 2002) are adopted to assess the impact of the studied heterogeneity factor on the failure propagation in the power-water CISs.

Failure scale refers to the number of nodes damaged during the simulated disaster. The impact of the heterogeneity factor on failure scale, denoted as $p_1$, can be calculated as follows:

$$p_1 = \left|\frac{n' - n_0}{n}\right| \quad (6)$$

where $n'$ and $n_0$ are the number of failed nodes of the modified model and baseline model, respectively and $n$ is the total number of nodes in the network.

Propagation time is measured by the number of propagation steps in the simulation before the network reaches a post-disaster steady state. Propagation time would attain a maximum value if a single node fails at every failure propagation step. The impact of the heterogeneity factor on propagation time, denoted as $p_2$, can be calculated as follows:

$$p_2 = \left|\frac{\eta - \eta_0}{n}\right| \quad (7)$$

where $\eta$ and $\eta_0$ are the propagation time obtained from the modified model and baseline model, respectively.

Node failure order refers to the failure propagation step at which the node fails. The failure order of all nodes in a system can be denoted as a sequence $\theta = (o_1 \cdots, o_m, \cdots, o_n)$ (the order of an operational node is 0). Taking $\theta^0 = ({o_1}^0 \cdots, {o_m}^0, \cdots, {o_n}^0)$ to be the node failure order obtained from the baseline model, the impact of the heterogeneity factor on failure order, denoted as $p_3$, can be calculated as follows:

$$p_3 = \sqrt{\sum_{m=1}^{n} (o_m - o_m^0)^2} \quad (8)$$

Larger values of $p_1, p_2$ and $p_3$ indicate larger impacts of the heterogeneity factor on the failure scale, propagation time and node failure order, respectively.

# 4 Case Study

## 4.1 Case Description

A case study of the interdependent water and power supply systems on the Tsinghua University campus was conducted to illustrate the impact of systemic heterogeneity on failure propagation across the CISs. The number and location of each CIS's facilities as well as the links between them were obtained from available design documents of both systems. The layout of both systems superimposed over the campus map is illustrated in Fig. 1. All facilities and major components of the two systems were regarded as nodes, whilst power cables and water pipes were regarded as links. A total of 86 nodes and 148 links were identified, as summarized in Table 2. Nodes belonging to the power supply network were labeled nodes 1 through 42, and those belonging to the water supply system were labeled nodes 43 through 86. In addition, there are two types of interdependency links in this case, and their layouts are presented in Fig. 2.

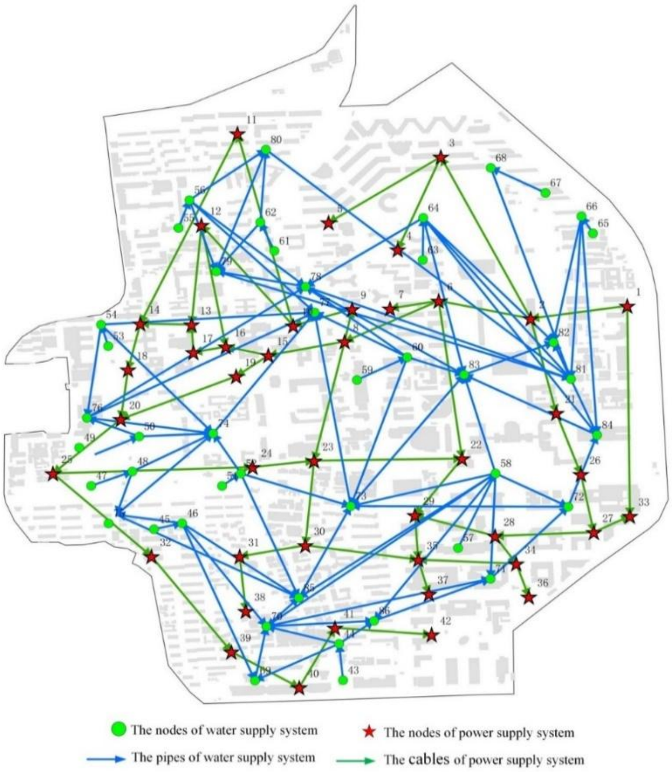


Figure 1: Layout of case systems

Table 2: Summary of facilities and connections in the case systems.

| System | Facility (acronym and number) | Link (number) | |
|---|---|---|---|
| | | Connectivity within systems | Dependency between systems |
| Power supply system | Electric substation - 110kv-10kv (ES,1)<br>Switching station (SS,12)<br>End user (EU,29) | Power cable (51) | Water pipe (1) |
| Water supply system | Groundwater well (GW,13)<br>Pump station (PS,13)<br>End user (EU,18) | Water pipe (83) | Power cable (13) |

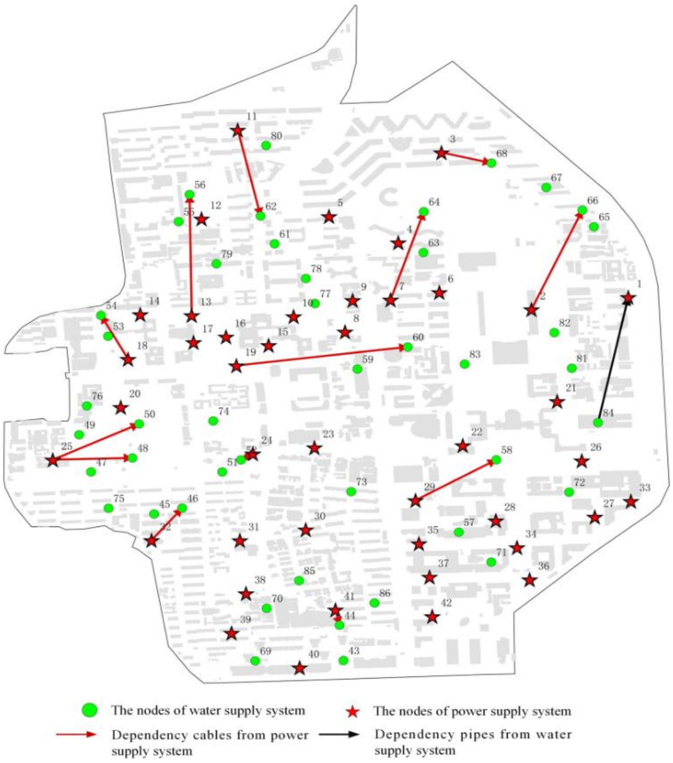


Figure 2: Dependency links of water and power supply system in study case.

### 4.2 Simulated Disaster Scenario

An earthquake scenario was chosen as external disruption. Peak ground acceleration (PGA) was the input parameter used to represent the earthquake disaster in simulation. PGA represents the ground motion induced by the seismic waves. According to the Seismic Ground Motion Parameters Zonation Map of China (2015), the PGA of Beijing is 0.3g, where g is taken as 10m/s2. It was assumed in the simulation that a node would fail when the inputted PGA value was larger than the seismic resistance of the component represented by this node. The seismic resistance of all facilities and major components (including ES, GW, PS and SS) was obtained from their design documents. Their values varied between 0.2g and 0.4 g.

## 5 Results and Discussions

The failure propagation of the power-water CISs was simulated, based on the baseline model and modified model respectively, using MATLAB. The simulation results are summarized in Fig. 3. As can be seen in the Fig. 3, the failure propagation patterns in the two models showed obvious differences. The baseline model propagated four steps to reach a steady state and a total of 21 nodes were damaged. In the modified model, only three failure propagation steps were necessary to bring the system to a steady state and the number of damaged nodes decreased by 10, which was nearly half of that observed in the baseline model. These results indicated that the impact of the studied systemic heterogeneity factor was considerable.

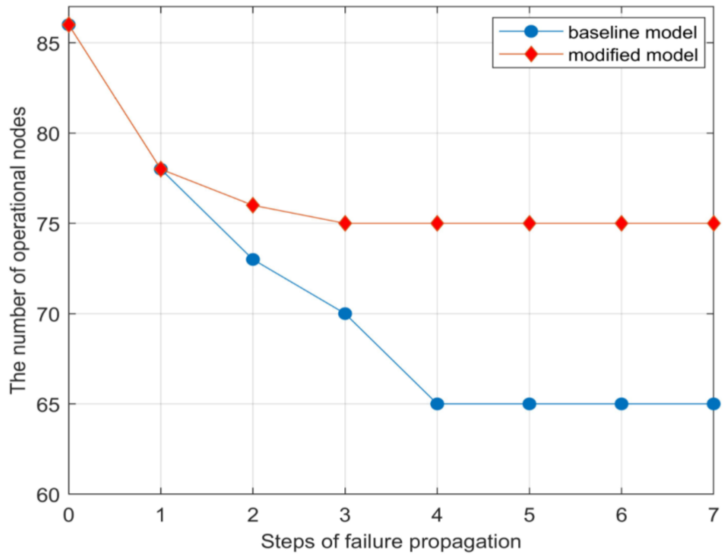

Figure 3: Failure propagation pattern observed in each model

Based on the simulation results, the failure order of every node in both models are summarized and presented in Fig. 4.

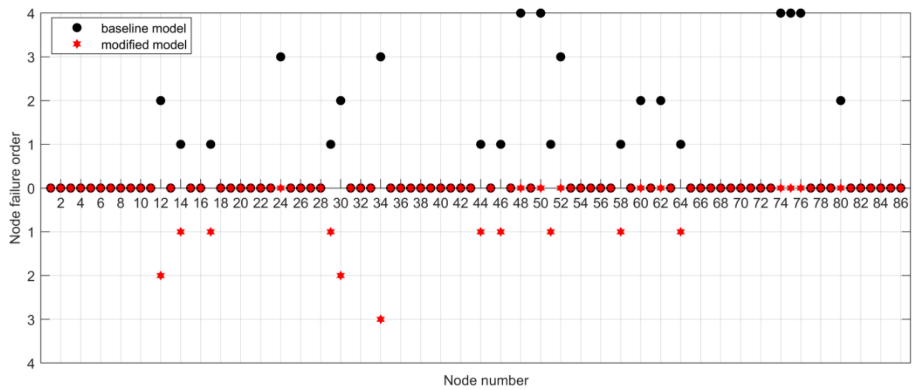

Figure 4: Node failure order sequence in each model

It can be observed from Fig. 4 that nodes 12, 14, 17, 29, 30, 34, 44, 46, 51, 58, 64 failed in both models. Among them, nodes 14, 17, 29, 44, 46, 51, 58 and 64 failed in the first failure propagation step of both models, whilst nodes 12, 30 and 34 failed due to the ripple effect of damages incurred from the seismic waves. Specifically, nodes 14, 17 and 29 were switching stations of the power supply system, nodes 44, 46, 58 and 64 were pump stations and node 51 was a groundwater well. These nodes failed in both models, which indicated that these components were highly vulnerable to earthquake.

In addition, based on the simulation results, the impact metrics were calculated and the results are presented in Table 3.

Table 3: Impact assessment results.

| Impact on failure scale (p1) | Impact on propagation time (p2) | Impact on failure order (p3) |
|---|---|---|
| 0.1163 | 0.0116 | 10.4886 |

Results from Table 3 show that the heterogeneity in system susceptibility to overload failure had a considerable impact on failure propagation across the power-water supply system. In the baseline model, 21 nodes failed, of which seven were from the power supply system and 14 were from the water supply system. However, when was heterogeneity factor was considered, only five nodes from the water supply system were damaged, which indicated that the disaster impact in the baseline model was overestimated.

Based on the assessment results obtained in this study, it can be reasonably inferred that systemic heterogeneity has a significant impact on failure propagation across interdependent CISs. This finding is consistent with the findings reported in related studies (Buldyrev et al., 2010; Buldyrev et al., 2011; Duan et al., 2019). Among these studies, a typical example is the work by Buldyrev et al. (Buldyrev et al., 2010), which simulated failure propagation through two tightly interdependent CISs each modeled using power-law degree distributions. The conclusions from their work was that the more heterogeneous the networks, the smaller the damage that can be sustained before functional integrity is totally compromised. Their results strongly support the conclusion of this paper, which argues that systemic heterogeneity indeed has an impact on failure propagation across CISs.

In this study, when systemic heterogeneity was taken into consideration, both power and water supply systems experienced less damaged nodes than in the baseline model. Failed nodes in water supply system were all damaged by the seismic waves since no overload damage could occur. As the number of failed nodes decreased in the water supply system, the number of damage nodes in power supply system also decreased because of the interdependency between them. This finding indicates that disaster impact would be overestimated if systemic heterogeneity were not taken into consideration, and also that the disaster impact of one system can be controlled by the state of other systems due to the interdependency existing between them. It is therefore important to design systems with reliable inner-dependency and interdependency links.

## 6 CONCLUSION

With rapid urbanization worldwide, modern CISs are becoming increasingly topologically networked and functionally interdependent. Every CIS has its unique physical network features, transported materials, operation mechanism and disaster response patterns, which differentiates it from other CISs. This systemic heterogeneity between CISs, particularly its impact on failure propagation, has been largely overlooked in prior research. This study therefore aimed at assessing the impact of systemic heterogeneity on failure propagation across interdependent CISs, by comparing simulation results for an AFB model in which a typical heterogeneity factor was considered, to that from a baseline model in which heterogeneity was not considered.

Results from a power-water CISs case study showed that the impact of systemic heterogeneity on failure propagation across interdependent CISs should not be overlooked. More specifically, the results showed that overlooking systemic heterogeneity could amplify the overall impact of a disaster event on the interdependent CISs, therefore, systemic heterogeneity should be appropriately incorporated when modeling failure propagation across CISs. In-depth knowledge on systemic heterogeneity and how to consider it in the modeling process is imperative to ensure the accuracy and reliability of models used in assessing disaster response behavior of CISs. Results from this study not only provided a better understanding of the three studied HFs but also highlighted the importance of addressing systemic heterogeneity in general when modelling CISs.

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# A REAL-TIME APPROACH TO EVALUATE OCCUPANTS' THERMAL COMFORT IN THE INDOOR ENVIRONMENT

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**Abstract:** Building performance analysis applications have focused on the evaluation of specific designs based on static, uniform indoor environments. In reality, people live in a dynamic environment, neither indoor environments nor building occupants are static, and that would make thermal sensation experienced by an occupant in a building unstable and challenging to evaluate through the time. The cur-rent field survey methodology to evaluate thermal comfort in buildings according to Performance Measurement Protocols for Commercial Buildings (PMPCB) is based on instrumental measurement of indoor climate and questionnaires to be answered by building occupants in a specific space at the exact time. Some studies have questioned this approach due to the inconsistency of physical measurement, sampling procedures, and doubtful estimations of some other variables. These are likely to contribute to the incredibility of the survey and possibly affect the overall prediction accuracy.

Nowadays, the advancement of IoT technology has the potential to transform human-building interaction and improve building energy performance. It has been estimated that the connected IoT devices are around 9 billion worldwide, and this number expected to grow to reach 50 billion by 2020. In the built environment, the ability to control building indoor environmental variables can have a substantial impact on improving indoor environmental quality and reducing energy consumption, such control mostly achieved by using sensor technology.

Thus, this paper presents a unique approach to measure real-time human thermal comfort in the indoor environment. The proposed approach can predict occupants' thermal satisfaction level of an indoor environment throughout the building's operation. The implementation of environmental sensors and a pilot run to evaluate thermal satisfaction in real-time has been tested. The thermal model in ASHRAE standard 55 has used to evaluate thermal comfort.

**Keywords:** Human thermal comfort, Smart buildings, Internet of things (IoT), Predicted mean vote (PMV), Built environment, Climate change, Building energy efficiency

## 1 INTRODUCTION

Nowadays, climate change is the biggest threat to human civilization, and it is happening as a result of human activity. Since the industrial revolution, the increase in Greenhouse Gas Emissions (GHGs) has led to a rise in global temperatures. The primary source of GHGs is from burning fossil fuel-based energy. Reducing the amount of energy required in our everyday life can significantly cut down human impact on the environment. The

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built environment (BE) considered as one of the largest emitters of GHGs and a primary contributor to climate change (Architecure2030, 2018, DOE, 2010, Asadi et al., 2012). Globally, buildings account for 40% of global energy consumption and contribute to more than 30% of CO2 emissions (Costa et al., 2013). This has led to a massive concern in the research community to conduct numerous studies to improve building energy performance in the BE, on new buildings, in design and construction of building envelopes such as thermal insulation (Pan et al., 2012, Joudi et al., 2013), lifecycle analysis (Asif et al., 2007) and optimization (Lam and Hui, 1996); on renovation of existing buildings (Chantrelle et al., 2011); and on optimization and control of HVAC and lighting systems (Mary Reena et al., 2018, Brooks et al., 2015).

The increase of energy demand in the BE connected to building occupants and the necessity of providing better comfort conditions, thermal comfort, visual comfort, acoustic and air quality (Pérez-Lombard et al., 2008, Nguyen and Aiello, 2013). Previous studies have shown the thermal conditioning system is among the major of energy end-use in the BE; it is responsible for about 50% of total energy consumption especially in non-domestic buildings (Pérez-Lombard et al., 2008, Chua et al., 2013, Ma et al., 2019). Another study on the evaluation of indoor environmental quality (IEQ) has shown thermal comfort satisfaction is highly important by building occupants and has a substantial impact on energy efficiency compared to other comfort needs (Frontczak and Wargocki, 2011). Accordingly, understanding thermal comfort implications on energy efficiency in buildings is essential not only to save energy and cut down energy bills, but it has a vital factor to mitigate human impact on global warming. As a result, several assessments and rating programs worldwide formed to promote sustainability and green buildings such as BREEAM, LEED and ENERGY STAR and becomes prevalent in the BE. Furthermore, architects and engineers use BIM and energy simulation tools to predict and improve building performance during the design stage of a building's lifecycle. Nonetheless, during building operations, where buildings consume up to 84% of total energy use in its lifecycle (DOE, 2010, Becerik-Gerber et al., 2011), buildings experience several unexpected factors that affect energy performance and occupants' thermal satisfaction such as sophisticated use of electrical equipment or occupants behavior.

Measuring thermal comfort in operational buildings is quite complicated and requires an in-depth perception of the environmental factors affects occupancy thermal satisfaction and cause overuse of energy. Most of the researchers have used the PMV index to evaluate thermal comfort in the indoor environment. This model also adopted by most of the standard and energy simulation tools. PMV index takes six parameters. Namely temperature, humidity air velocity means radiant temperature, metabolic rate clothing insulation. The knowledge of existing standards to evaluate IEQ is an example of this complexity. Accordingly, most works in this area carried out a qualitative analysis based on people performing some activity and answering a questionnaire.

Therefore, this paper aims to present an innovative approach to measure occupants' thermal comfort in the indoor environment and predict energy-use in real-time. The wireless sensor technology used to obtain environmental information, including Ambient temperature, relative humidity and air velocity at every single zone of the indoor environment. The proposed approach does not affect room layout or occupant's activity in the space.

## 1.1 Thermal comfort in the built environment

Thermal comfort is an essential factor in building design and in operating of indoor environment and its effect directly to occupants' satisfaction and energy consumption.

Moreover, the energy used to provide thermal satisfaction is high; around 70% of primary energy use in commercial buildings goes for heating and cooling systems.

The reason for this poor performance related to several factors in the design and operation of the building. Such as building envelope design, the efficiency of the mechanical system and controls. Besides, there is a limitation or weak undressing among designers and building operators about the range of factors that are possibility affect the indoor thermal condition. Understand thermal comfort condition can create an excellent opportunity to save energy while maintain or even improve the level of occupant satisfaction.

Introducing such approach can give a clear understanding of how human response to the indoor climate variables. The current thermal comfort prediction tool can support the designer and building operators to understand human thermal comfort. However, these tools are static and based on manual measurement/input depends on designer/operators understanding of indoor climate variables.

The main objective of this paper is to present a novel approach to evaluate thermal comfort according to ASHRAE standard 55 in a single zone. Different from other thermal comfort tools, the main feature of this approach is to evaluate occupancy satisfaction and predict energy-use in real-time. The implementation of this approach can benefit architect, engineer and building operators and better understand thermal comfort.

## 1.2 Sensor technology

Nowadays, the advancement of IoT technology has the potential to transform the BE and the way building occupants interact with their surroundings. It has been estimated that the number of connected IoT devices are about 9 billion worldwide, and this estimate is expecting to grow to reach more than 50 billion in the next few years (Gubbi et al., 2013). In the BE, the ability to control environmental variables can have a substantial impact on improving the indoor environment and reducing energy consumption, this method of control often performed by using sensor technology (Dong et al., 2019). Several sensors are being used in the BE, whether to understand occupants behavior pattern or to study the characteristic of the indoor environment. In building operation, these sensors can be categorized into three types; a) occupancy sensors to collect data from building users such as Passive Infrared Sensor (PIR) and Ultrasonic sensor, b) Sensors that can be used to collect data from the environment such as temperature, humidity and CO2, c) Personal IoT sensors such as wearable sensors, heart rate, etc. A smart sensing system for thermal comfort can be classified into two classes, 1) human centre studies and 2) environmental measurement.

In the area of in human-centric design where age, gender and body mass are considered to determine individual thermal comfort, ambient temperature sensor and wearable are used. One of the biggest challenges in these studies is that individuals' thermal sensation is varied among occupants, and there is no fixed point in which all occupants feel comfort (Abdallah et al., 2016, Liu et al., 2013, Linhart and Scartezzini, 2011, Corgnati et al., 2008). To this end, Yun and Won (Yun and Won, 2012) introduce a personal comfort system to measure individual thermal comfort and save energy using developed with the integration of temperature, humidity, and air velocity sensors, the char works as a macro-zone controller. (Sardini and Serpelloni, 2010) uses a wireless sensor network (WSN) to determine the indoor temperature. The sensor attached to the electromechanical generator, which is powered by the indoor air velocity.

This research is looking onto design a real-time approach enables researchers, building's operator to collect environmental parameter and occupants' thermal satisfaction of a single zone in real-time for better decision making and avoid unnecessary energy consumption.

## 2 METHODOLOGY

Usually, building performance analysis applications have focused on the evaluation of specific designs based on static, uniform indoor environments. People live in a dynamic environment, neither indoor environments nor building occupants are static or uniform, and that would make thermal sensation experienced by an occupant in a building unstable, complicated and nearly impossible to evaluate. Moreover, thermal comfort-energy conservation requires an advance understanding of the occupant's comfort level in the indoor environment.

This study has established a new approach of thermal comfort-energy sensing using a developed IoT sensor and data analytics technique using a machine learning (ML) regression model to predict the energy-consumption in real-time. This approach can help the building's operator to evaluate occupant's thermal satisfaction and make the building more energy efficiency. Although many design measurements considered building energy performance factors, finding the right balance between energy performance and occupancy thermal satisfaction in the operation of buildings is absolutely challenging. The current thermal comfort model in the international standards is used for evaluation of the indoor environment for a short period. Furthermore, there is a weak understanding of the relationship between occupants' thermal comfort and the amount of energy consumption related to them.

The thermal comfort-energy evaluation approach proposed in '**Erro! Fonte de referência não encontrada.**' contains two modules. The first module is the evaluation of occupants' thermal comfort, which includes the characteristics of the indoor environment associated with thermal comfort returned by the developed IoT sensors. The data collected from the sensors are being used in the thermal comfort model in ASHRAE 55 standard to predict the level of occupant's satisfaction. A function has been developed to calculate PMV values in real-time based on the tool published by CBE University of California (Schiavon et al., 2014). However, this study has only considered the environmental parameters for the evaluation of thermal comfort, the personal factors are established based on the function of the space to set the level of activity, and the time of the year to set the type of clothing insulation.

The second module is the energy prediction. The prediction module consists of data generation and data machine learning. In order to predict the energy performance of a single zone in the building, an energy simulation tool has been used to generate synthetic data for that zone, considering all the possibilities of energy-use. in the simulation two types of data used as input static and parametric. Static data include 1) the energy model of the building considering all the properties of building components construction and the type of opening; 2) weather data information.

Parametric data include operation schedules for heating and cooling, occupancy schedule, and humidity control. This study has focused on the source of energy from the heating and cooling system in the building. Thus, any source of energy not related to the thermal conditioning system in the building has been disabled in the execution of the simulation, such as lightings, computers, and office equipment.

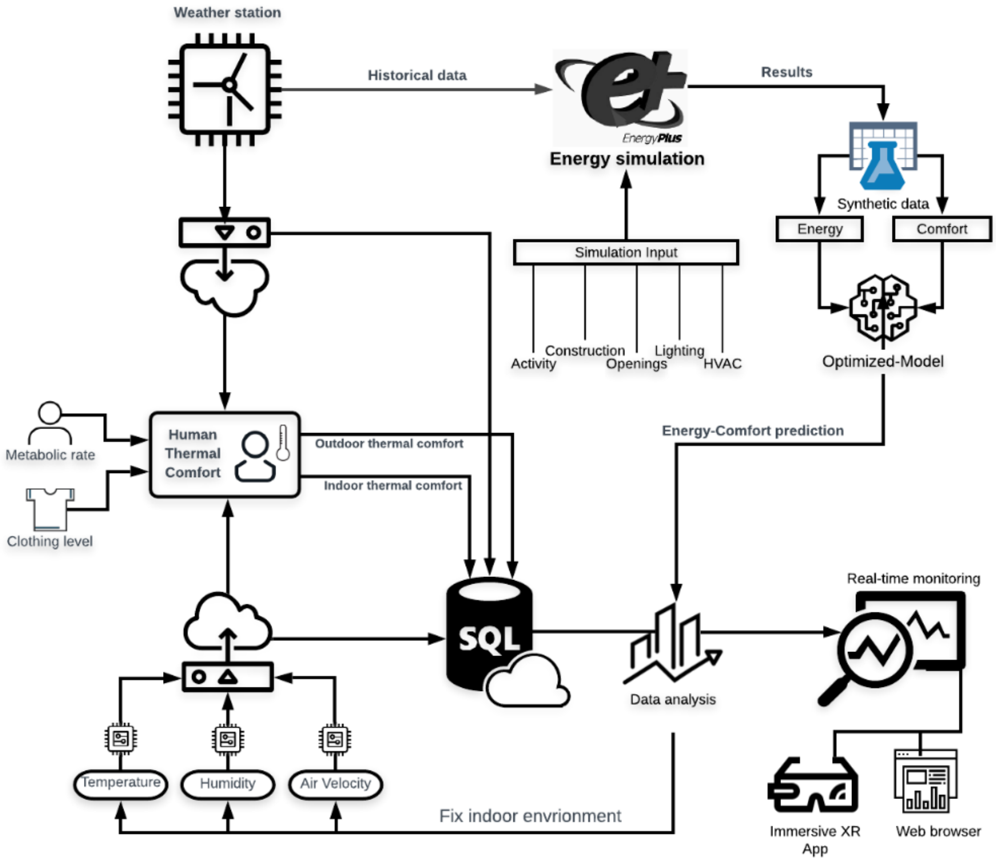


Figure 1: Energy-thermal comfort evaluation approach

## 3 DESIGN OF REAL-TIME THERMAL COMFORT EVALUATION APPROACH.

There are several tool and applications used to measure thermal comfort, such as climate consultant, Ecotect weather tool, Designbuilder, AHERAE thermal comfort too(Hudson and Velsaco, 2018). These applications need weather files which include one-year historical data. The main feature of these tools is to help read and understand weather data and show a summary of the selected weather file. It enables users to suggest strategies and techniques for better energy efficiency building, each of which based on its climate. In general, it centres on climate analysis rather than human thermal comfort, Moreover, it does not reflect the latest standard (Schiavon et al., 2014).

To this end, there is a need to developing a thermal comfort sensor that can aid building users and operators to understand occupants' thermal behaviour and assist them in applying the right strategies to minimize energy end-use. Thus, this study has proposed a real-time thermal comfort evaluation approach to predict energy consumption in the indoor environment.

### 3.1 System architecture

The proposed system can be divided into three layers: a) data acquisition using IoT sensors (Physical); b) data storage and data processing (back-end software), and c) data visualization (front-end software) see '**Erro! Fonte de referência não encontrada.**'.

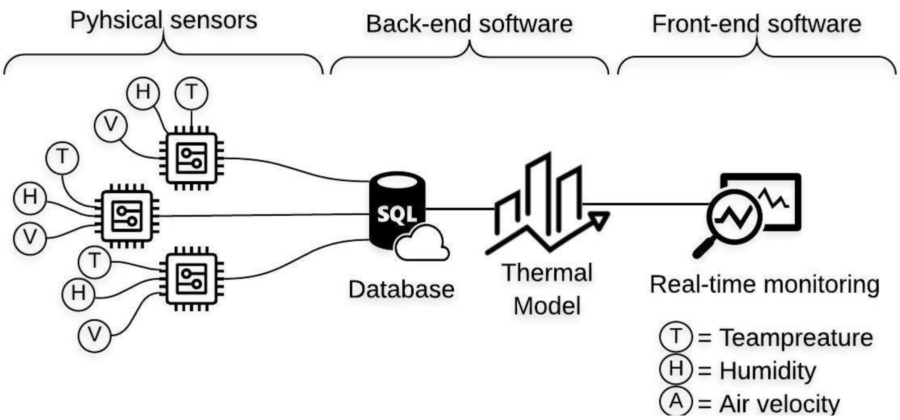


Figure 2: System overview

The physical layer includes environmental sensors to measure attributes from the indoor environment. The implementation consists of commercially available sensors to capture human thermal comfort environmental-related data through a Wi-Fi module that provides two-way data transmission, sent and receive. The sensors used in this study include temperate, humidity, air velocity, and Wi-Fi module (see Figure 3). All environmental sensors are powered by five voltage from a power bank using a standard Universal Serial Bus (USB) cable and connected to the internet using the Wi-Fi module.

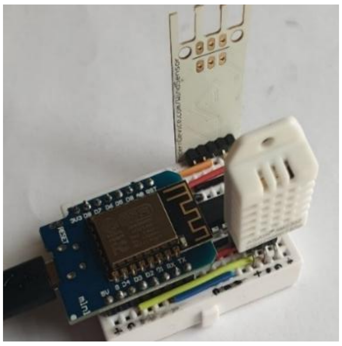

Figure 3: Thermal comfort sensor

The back-end software includes client read values from physical sensors over Wi-Fi and transmit it every 30 seconds. The client sends data from sensors and stores them in the cloud database. The data is stored in a separate table for each type of sensor in the cloud. This study is also using web page programming languages, HTML, JavaScript, and jQuery to control the data. Furthermore, this study has developed a thermal comfort model based adopted from CBE's comfort calculator following ASHRAE standard 55. The developed model receives environmental values from sensors temperature, humidity, and air velocity and evaluates occupants' thermal satisfaction. In the developed thermal comfort model personal values metabolic rate and clothing level are fixed according to the general activity in the space and the season of the year see **Erro! Fonte de referência não encontrada.**.

The front-end software is using data stored in the cloud database for representation and user interaction. A flexible visualization technique is required to accommodate sensors data. There are several visualization techniques presented by previous studies that can be utilized for representation. An immersive visualization technique is still under development. The proposed thermal comfort evaluation system shows one of the IoT applications. It enables building users to observe the level of occupants' satisfaction in space in real-time.

Table 1: Example of clothing insulation and metabolic rate values

| Activity | Metabolic rate (met) | Clothing level | Insulation values (clo) |
|---|---|---|---|
| Reading seated | 1.0 | Typica summer indoor | 0.5 |
| Typing | 1.1 | Trouser, long sleeve shirt | 0.61 |
| Standing relax | 1.2 | Jacket, Trouser, long sleeve shirt | 0.96 |
| Walking | 1.7 | Typica winter indoor | 1.0 |

## 3.2 Predicted Mead Vote in thermal comfort calculator

The proposed thermal comfort calculated in this study is based on the classic steady-state model for air-condition spaces proposed by Fanger, Predicted Mean Vote (PMV) index model (Fanger, 1970). The PMV model aims to predict the thermal sensation of occupancy in mechanical ventilated space. Fanger's model measured using four environment factors and two personal factors. The environmental-related factors are temperature, mean radiant temperature, air velocity, and humidity. The personals factors are metabolism and clothing. The calculation of the PMV values, as follows (Fanger, 1970).

$$PMV = (0.028 + 0.3033e^{-0.036M}) \times L \quad (1)$$

$$L = (M - W) - 3.05 \times 10^{-3}[5733 - 6.99(M - W) - P_a] - 0.42[(M - W) - 58.15 - 1.7 \times 10 - 5M5867 - Pa - 0.0014M34 - ta - 3.96 \times 10 - 8fcltcl + 2734 - tr + 2734 - fclhc(tcl - ta) \quad (2)$$

$$t_{cl} = 35.7 - 0.028(M - W) - 0.155I_{cl}\{3.96 \times 10^{-8} \times f_{cl}[(t_{cl} + 273)^4 + tmrt + 2734 + fcl \times hc(tcl - ta)\} \quad (3)$$

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25}, & \text{if } 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{V} \\ 12.1\sqrt{V}, & \text{if } 2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{V} \end{cases}$$

$$f_{cl} = \begin{Bmatrix} 1.00 + 1.290 I_{cl} \text{ for} \\ I_{cl} \le 0.078\ \text{m}^2\text{K/W} \\ 1.05 + 0.645 I_{cl} \text{ for} \\ I_{cl} > 0.078\ \text{m}^2\text{K/W} \end{Bmatrix} \quad (4)$$

(5)

Where M: metabolic rate (W/m$^2$)

W: external work (W/m$^2$) (assumed to be 0),

$I_{cl}$: clothing insulation

$f_{cl}$: clothing factor, ta: air temperature (°C)

$t_r$: mean radiant temperature (°C),

v: air velocity (m/s)

$P_a$: vapor pressure of air (kPa)

$h_c$: convective heat transfer coefficient (W/(m$^2$K))

$t_{cl}$: surface temperature of clothing (°C) e: Euler's number (2.718)

The PMV model has a seven-point scale see **Erro! Fonte de referência não encontrada.**; it's recommended that the PMV value should lie within -0.5 to +0.5 to ensure the best thermal comfort by most occupants.

Table 2: PMV thermal sensation scale

| PMV | Sensation |
|---|---|
| +3 | Hot |
| +2 | Warm |
| +1 | Slightly warm |
| 0 | Neutral |
| -1 | Slightly cool |
| -2 | Cool |
| -3 | Cold |

## 3.3 Energy prediction

The energy prediction in this study based on the generation and ML training of multiple synthetic data of a specific space in the building. The Design builder has been used to generate an hourly prediction of PMV index, Indoor Air Temperature, indoor Relative Humidity, and energy consumption for one year. An ML regression model using the decision forest algorithm presented by (Criminisi et al., 2012) is used to train the generated synthetic data of the energy simulation. Then, the trained data from the regression model was used to predict the energy consumption of the indoor environment based on the collected environmental attributes from the distributed IoT thermal comfort sensors (see Figure 4) the overview of the energy prediction workflow.

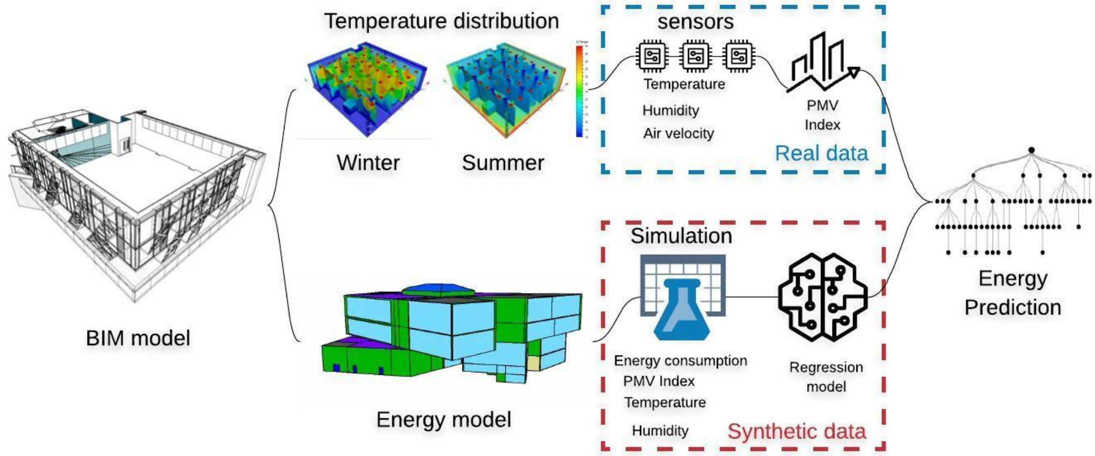


Figure 4: Overview of energy prediction workflow

# 4 IMPLEMENTATION AND RESULTS

The proposed approach implemented in a postgraduate (PGR) office environment at a University of Huddersfield, UK, where occupants are acting naturally without any interference by the researcher. The office is about 240 m2. The main activity is stationary office work. The ventilation system includes a heat recovery unit (HRU). Several CFD simulations have been performed to understand the temperature distribution of the space in the peak climate conditions in winter and summer. The heat map of the temperature distribution in the studied indoor environment can support the decision of placing the thermal comfort sensor see 'Figure 4'. However, in this experiment only one sensor has been used.

The energy model has been developed for the entire building considering orientation, construction properties, opening, and HVAC systems in the building. During the execution of the energy simulation, only PGR office is measured for energy use, air temperature, radiant temperature, relative Humidity, and Fanger PMV. The implementation of the decision forest regression model requires training and testing data. Thus, the data from energy simulation has been divided into two sets 70% used in the training and 30% for testing. The results from the trained model have displayed the mean absolute error is 0.676479, and the coefficient of determination is 0.914263. Comparing the results from prediction and original data from the simulation, it shows some false in the prediction see 'Figure 5'. This can be fixed by adding more parameter and generating more dataset for training.

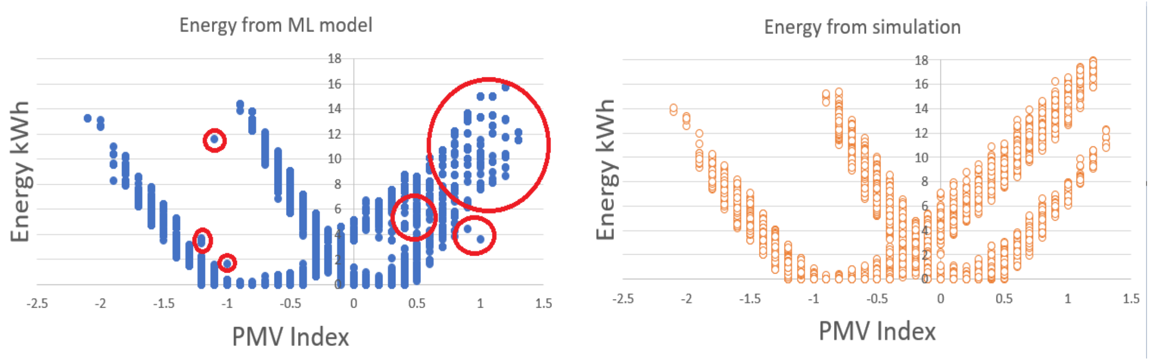


Figure 5: Compare the results from prediction and simulation

## 5 Conclusion

In this study, a thermal comfort model sensor has been developed to predicted occupants' thermal satisfaction within the indoor environment. Three sensors used to collect environmental parameters, temperature, humidity, and air velocity. A Wi-Fi module to receive and transmit the sensors data to a cloud database. An online developed thermal comfort evaluation model is used to calculate PMV values in real-time. The system also includes ML trained model to predict the amount of energy used for heating and cooling in the indoor environment.

The output of the presented approach comprises two types of data real and synthetic. The real data are captured from the indoor environment. These data are being collected from the developed thermal comfort sensors. The synthetic data generated from energy simulation include hourly energy performance, indoor climate, and thermal comfort of the studied environment. The ML decision forest regression algorithm is used to predict energy use. The experiment has some limitation which can be listed as follows:

- Using one thermal comfort sensor is not adequate to accurately estimate thermal comfort in the studied environment, the CFD simulation has shown multiple thermal zones need to be included in the study.

- The mean absolute error of the trained model is not good enough for an accurate prediction and it has some false prediction. Hence, it requires more data to improve the accuracy of the prediction.
- The thermal comfort sensor is consuming more energy than expected. The developed system is transmitting data every 30 seconds, and that would make the power bank loses its power in less than four days.

Future work will focus on improving the ML prediction model by providing more synthetic data. Parametric simulation is going to be considered to build an optimization model to predict the optimum environmental attribute to minimize energy use for heating and cooling.

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# EVALUATION OF MULTI-SKILLED LABOUR IN AN OFF-SITE CONSTRUCTION FACILITY USING COMPUTER SIMULATION HYBRID APPROACH

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**Abstract:** Off-site construction uses production lines to produce building components in a controlled factory setting. By shifting construction activities to an off-site environment, many manufacturing principles can be employed, including the use of simulation to predict production's performance and the impact of different labour arrangements. Typically, each workstation has a specialized labourer working only at the one station. Those workstations in the production line with the longest productive and wait times highly influence the throughput of the line. Often, some labourers are sitting idle while other stations are backlogged. Despite being successfully applied in offsite construction production lines, discrete event simulation fails to mimic construction task's accurately when submitted to the effect of multi-skilled labourers floating through different workstations during work. This paper investigates a hybrid approach where discrete event and continuous simulation are combined in a hybrid approach to predict the impact of multi-skilled labour to reduce idle times and increase productivity by balancing cycle times. Take-off quantities from historical data are used as an input to the proposed hybrid model to determine the required duration and locations of multi-skilled labourers in the production line. Furthermore, the optimal number of multi-skilled labourers is found by balancing the costs of training multi-skilled labourers with facility overhead costs.

**Keywords:** Simulation, off-site construction, productivity, multi-skilling.

## 1 INTRODUCTION

Shifting construction to off-site facilities has become increasing popular due its productivity, quality, efficiency, and safety benefits (Modular Building Institute 2010). This is achieved by borrowing concepts and knowledge from the manufacturing industry (Zhang et al. 2016). Modular construction is a popular method of off-site construction in which building components are constructed into two dimensional panels, then the panels are assembled into a volumetric unit either in the factory or on-site.

Traditionally, project management assigns labourers with individual specializations to each workstation and the modules are built across the production line. Labourers do not migrate from their assigned stations, which results in bottlenecks at the workstations with the greatest work content, and in turn this has substantial impacts on the progress rate of

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projects (Arashpour et al. 2014). Moghadam (2014) identifies production levelling, scheduling, and production flow as key areas of focus to improve the manufacturing process. In each of these areas, the implementation of multi-skilled labour is suggested by using of a group of multi-skilled labourers to support stationary labourers and adjust takt times to better handle the variability of projects and allow for non-fixed activity durations. Wongwai and Malaikrisanachalee (2011) also argues that multi-skilled labour resources decrease project duration, increase job stability for workers, and allow for higher flexibility in task assignment.

Arashpour et al. (2014) analysed process integration strategies for the utilization of multi-skilled and found that borrowing labourers from underutilized workstations smooths the capacity imbalance in the overall production line. If the production process is found to have workstations with a high variability in production times, then indirect skill chaining (multi-skilled crews that operate over a limited zone of the production line) is the optimal solution. This group of multi-skilled labours is required to move into any station along the production line as needed. The upstream migration of multi-skilled personnel through the production line would balance labour requirements and reduced lead time of a module. The multi-skilled provides a flexible allocation of resources into the most complex stations (longest duration), which will allow for complex products to be produced at a similar pace as the simpler products.

Despite advantages in productivity, the impact to train labourers to be multi-skilled must be balanced with the production gains, as there is still a lack of quantitative evidence regarding the trade-off of this strategy (Nasirian et al., 2019). Moreover, Ahmadian et al. (2016) argues the possible salary increase for multi-skilled labourers hinders further adoption of this strategy. Hence, there is a clear need for a systematic method to address the use of multi-skilled labour in modular construction facilities. This paper proposes an experimental approach using simulation as a surrogate system to address the impact of multi-skilled labour in offsite construction manufacturing.

Computer simulation is an effective tool that can be used to evaluate scenarios such as the effect of multi-skilled labour in production. Discrete event simulation (DES) is used to evaluate production scenarios in a virtual environment prior to real production (Altaf et al., 2018). Studies have been published using simulation in modular construction manufacturing to assess various risk factors (Li et al. 2014) and system efficiency (Hammad et al. 2002). In both previous works, DES is effectively applied as task durations are determined by a series of factors of discrete nature and by discrete steps. However, this approach is not suitable to address events in which durations are affected continuously and are not changeable due to the start or finish of an occurrence such as multi-skilled labourers working in-and-out of workstations as demand is impacted by events simulated.

In this context, Antonelli et al. (2018) presents continuous simulation as an approach where systems and events are modelled based on feedback loops within itself thus being an effective manner to model events impacted by multi-skilled labourers. Despite the ability of continuous simulation to model events affected by feedbacks loops, Barlas and Özgün (2018) points out that DES is better suited to model queueing systems due to the randomness of events based on stochastic distributions. Brito et al. (2011) indicates the combination of discrete event and continuous simulation, referred to as hybrid simulation, is potentially the optimal approach for problems when simulation requires both a low level of abstraction (e.g., predicting a start and end to a task based on randomness provided by DES) and a higher level of abstraction (e.g., a dynamic change to the production rate of an activity due to an increase or decrease of resources).

Barkokebas et al. (2015) evaluated the effect of incorporating dynamic workstations (workstations comprised of multi-skilled labourers) for the floor and wall production lines in an off-site construction facility. The study used discrete event simulation (DES) and continuous simulation to prove that multi-skilled labour balanced fluctuations in workflow and improved overall production without increasing the number of labourers. While multi-skilled labour was found to shorten production time, questions remain with respect to the added cost of hiring and training highly skilled labourers. Hence, this study still lacks information regarding the financial impact of the use of multi-skilled labour in the production line. In fact, the financial impact is addressed as a multi-dimensional problem in which there is a significant investment and still no clear trade-off between investment and benefits in this solution. Moreover, other aspects are also important to address such as space constraints; each station is limited by the amount of space available, which limits the number of workers performing simultaneously at a given time.

This paper aims to address the features of both DES and continuous simulation to better model the impact of multi-skilled labour in offsite construction manufacturing. The objective is to determine the optimal number of multi-skilled labourers in the facility and quantify the line balancing, lead time, and productivity benefits from the introduction of the multi-skilled labourer(s). Based on material data gathered from Moghadam (2014) at an offsite construction facility, and the results generated from discrete and continuous (hybrid) simulation, multi-skilled labour will be evaluated on a cost-benefits basis.

## 2 Methods

The methods applied in this research are presented in this section and summarized in Figure 1 below. The plant layout containing the number of stations and its precedence is modelled along with the respective number of resources (i.e. fixed labour) for each. Man-hour requirements are added in the model through a labour database that calculates the labour requirements dependent upon project's attributes such as size, number of elements, etc. Hourly cost for direct (fixed and multi-skilled labour) and indirect (factory overhead such as utilities, space rental, etc.) labour are added in the model so a financial assessment can be performed. A comparison between the current and potential improvements in time and cost are important criterion to determine a good trade-off for the use of multi-skilled labour in the production line while space constraints (e.g. maximum number of labourers that can fit in a station) help determine the feasibility of each scenario. The shift length determines how often multi-skilled labourers are allowed to move between stations and how long they will work in there. Moreover, the research is based on two assumptions: (1) the productivity of fixed and multi-skilled labour is the same, and (2) there is no space constraint between stations (i.e. stations will not stop work due to queue length ahead).

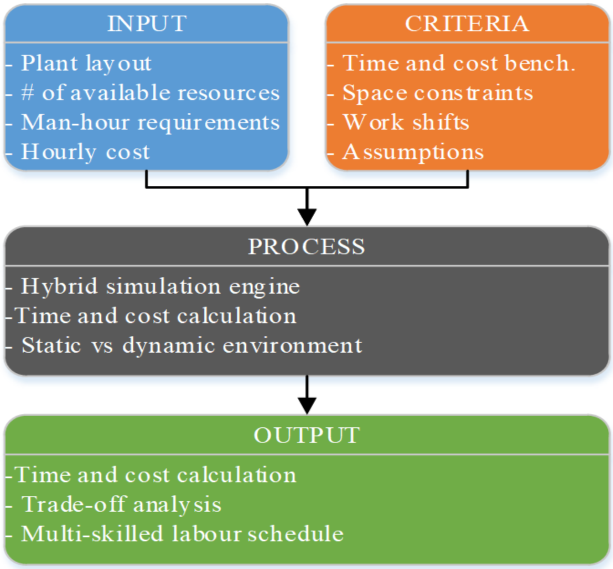


Figure 1: Methods overview

With all this information at hand, man-hour requirements for each project are added to the simulation engine, which consists of a combined discrete and continuous environments (hybrid). As per the given layout, projects are modelled as entities in a discrete environment while fixed (workers which won't leave their stations) and multi-skilled labourers are also modelled as discrete resources. The interaction between both environments for any simulated task is demonstrated in Figure 2 in which the database containing the man-hour requirements for each simulated task is connected to the simulation model developed in Simphony.NET and triggered at the discrete environment. After started, the number of fixed labourers and man-hour requirements for the task are sent to the continuous simulation environment which initiates an interaction with the multi-skilled resource pool at the discrete environment. Through each work shift, the task is performed at the continuous environment which requests multi-skilled labourers from the modelled pool at the DES environment, assigns these labourers as per Equation 1 and sends them to the continuous environment where the production rate is calculated as per Equation 2. Task man-hour requirements are deducted from the calculated production rate at each shift until it reaches to zero (i.e. end of task) and its final duration is calculated as per Equation 3 and added to the database.

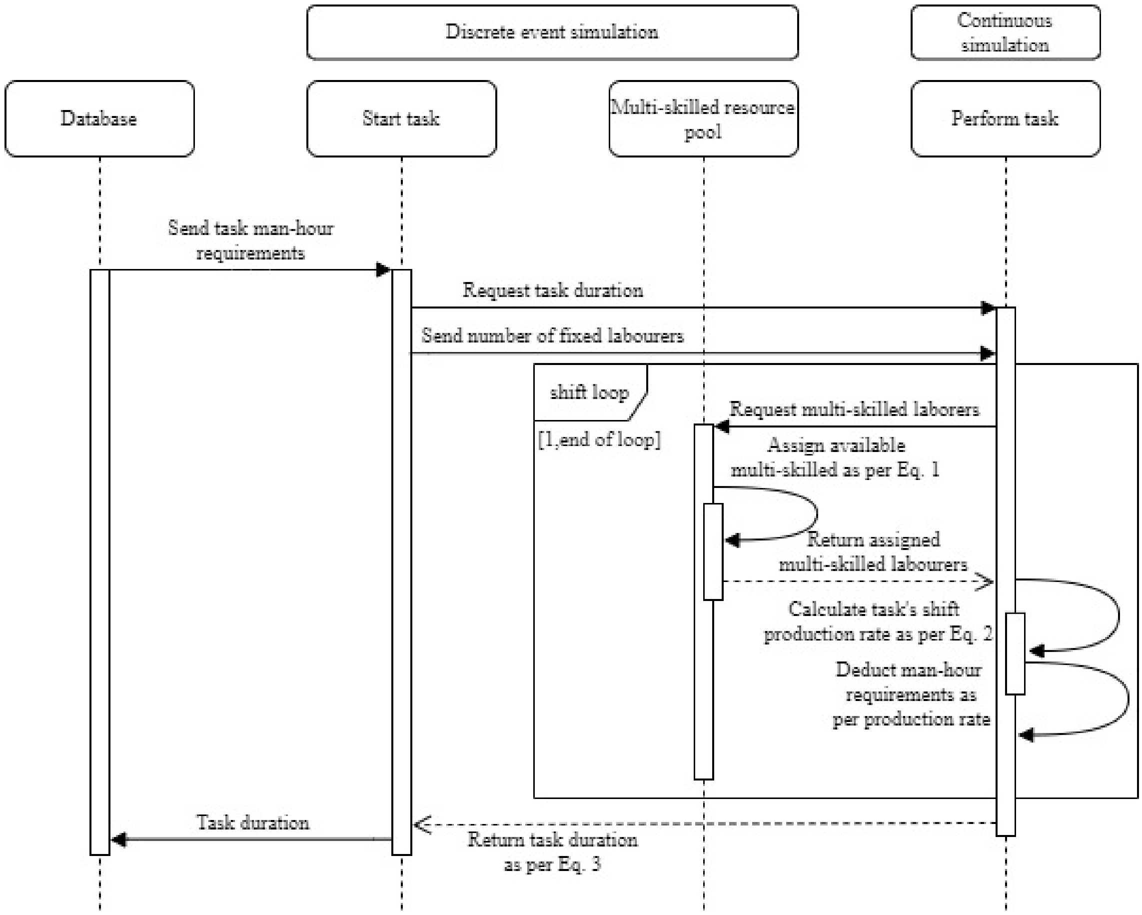


Figure 2: Sequence diagram between discrete event and continuous environments for a simulated task

$$\text{Station}_i = \text{Max}\left(\frac{Mhr_i^1}{P_i^1} + \cdots + \frac{Mhr_i^n}{P_i^n}\right) \quad (1)$$

$$P_i^n = f_i^n + m_i^n \quad (2)$$

$$Duration^n = \sum_1^i \frac{Mhr_i^n}{P_i^n} \quad (3)$$

where:

$Station_i$: Station where the multi-skilled labourer will work at shift i

$Mhr_i^n$: Task man-hour requirement of station n at shift i

$P_i^n$: Production rate at station n at shift i

$f_i^n$: Fixed labour at station n at shift i

$m_i^n$: Assigned multi-skilled labour at station n at shift i

$Duration^n$: Total duration of station n

As per Equation 1, the multi-skilled labourer is assigned to the station with the highest amount of man-hours left taking in consideration the production rate at each station as per Equation 2 representing the labour assigned (fixed and multi-skilled) at the given time assuming fixed and multi-skilled labour have the same productivity. In order to make scheduling of multi-skilled labour a realistic effort for modular contractors, Equation 1 is applied to each available multi-skilled labourer at the beginning the production line's shift (i.e., where each multi-skilled labourer should work for the given shift). Moreover, the logic for the allocation of multi-skilled labour is also dependent of the context provided in the given layout, such as space constraints, and which stations should allow for the use of multi-skilled labour as will be discussed in the next section. After the task is performed, total duration is calculated as per Equation 3 and the project (simulated entity) moves to the next station.

The total cost is calculated as per Equations 4, 5 and 6 below taking in consideration the direct and indirect costs incurred from the use of multi-skilled labour in the production line. Due to its extra training and expertise, it is assumed multi-skilled labour has a higher hourly rate paid by the employer. As observed in the equations below, the total cost consists of the sum of direct and indirect cost, which is represented by the product of man-hours spent by fixed and multi-skilled and its unit rates and factory's overhead represented by the product of total production time and factory's hourly overhead rate.

$$Total\ Cost = \text{Direct Cost} + \text{Indirect Cost} \tag{4}$$

$$Direct\ Cost = MHr_f \times \$_f + MHr_m \times \$_m \tag{5}$$

$$Indirect\ Cost = T_m \times \$_i \tag{6}$$

where:

$Total\ Cost$: Total cost in production line

$Direct\ Cost$: Cost incurred from labour in all stations

$Indirect\ Cost$: Cost incurred from overhead and fixed cost from the factory

$MHr_f$: Total man-hours worked by fixed labour in all stations

$\$_f$: Hourly rate for fixed labour

$MHr_m$: Total man-hours worked by multi-skilled labour in all stations

$\$_m$: Hourly rate for multi-skilled labour

$T_m$: Total simulation time

$\$_i$: Hourly rate for factory's overhead

By collecting station times and total cost, different scenarios are calculated by changing the number of available multi-skilled labourers in the simulated environment starting from a static (no multi-skilled labour) and moving to a dynamic (use of multi-skilled labour) environment. After simulation is performed, the results are analysed as a trade-off between the overall cost and time spent to manufacture all simulated projects. After selecting the best scenario, a schedule is provided for each multi-skilled labourer indicating which station he should be at during each worked shift. The presented methods will be better described in the next section through a case study.

## 3 CASE STUDY

The case study consists of a wood-frame modular facility in Edmonton, Alberta, Canada with labour intensive operations that rely on a few cranes and traditional construction equipment. The introduction of multi-skilled labour can represent a significant improvement in production lines such as this in which workers are the main driver of production. Figure 3 demonstrates the addressed layout in this paper with its stations and respective fixed resources.

The first identified bottleneck in the addressed layout is Station 2 since, in order to begin, both Stations 1a and 1b need to be completed (i.e., if one finishes before the other, it will remain idle while Station 2 will also be waiting for work commencement). The other identified bottleneck is in Station 3 due to idleness in the preceding Stations 1c and 2 when one finishes before the other, which potentially affects the remaining production. Hence, this research will evaluate the impact of multi-skilled labourers at the wall, floor, and roof framing stations (1a, 1b and 1c, respectively), which are considered the bottlenecks of the production line as highlighted in Figure 3 below.

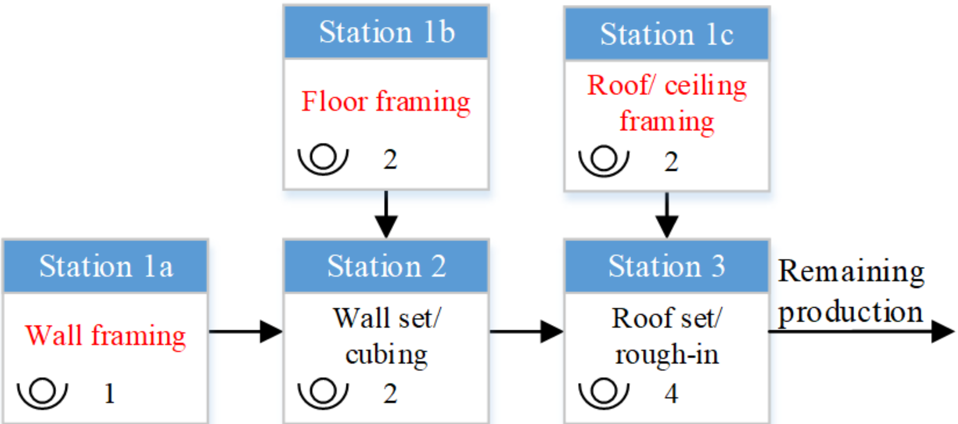


Figure 3: Addressed layout in the case study

The simulation model is first run with a scenario in which no multi-skilled labours are used (static scenario) in order to determine the current state of the production facility as a benchmark cost and timewise. After the benchmark is established, the simulation is re-run under different (dynamic) scenarios in which fixed labour is substituted by multi-skilled labour (i.e. Station 1c will be given one fixed and multi-skilled labour) and multi-skilled labourers are added in the production line. Based on the given layout and resources allocated, the logic for allocation of multi-skilled labour is demonstrated in Figure 4 below.

As demonstrated in Figure 4, the roof station is given preference for the use of multi-skilled labour if the walls and floors of the project are already finished. If that is not the case, the work to be performed in the addressed stations (wall, floor and roof stations) are compared and the multi-skilled labourer will help the station that satisfies Equation 1 at the given time. This analysis is simulated for every multi-skilled labourer at the end of each shift. In this particular facility, workers work a total of 8 hours a day divided into 4-hour shifts.

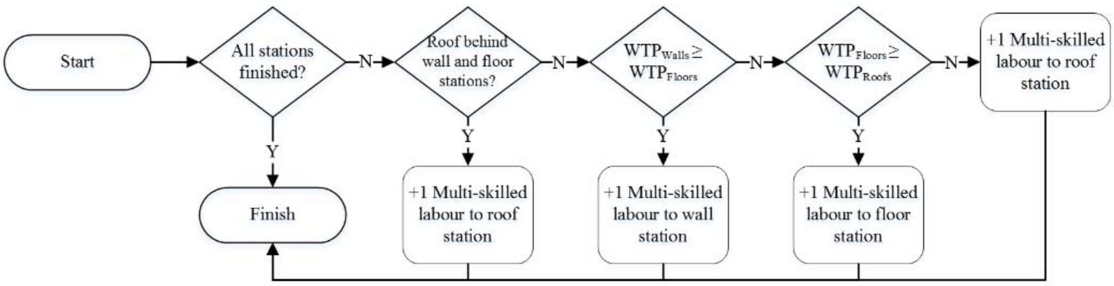


Figure 4: Proposed logic for multi-skilled labour

Man-hour requirements for each station and project are added in the simulation model from a labour database containing time studies performed as per statistical analysis in the case study manufacturing facility by Moghadam (2013). The projects, and their man-hour requirements for each station are described in Table 1 below, which consists of a combination of residential, commercial, and office spaces built using wood-frame structural members. The order in which these projects will be manufactured, and their impact in balancing the production, will not be addressed in this research as this decision is not taken by the production team but rather based on commercial and client deadline requirements.

Table 1: Projects addressed in case study

| ID | Total Area (m2) | Total man-hours per station | | | | |
|---|---|---|---|---|---|---|
| | | 1a | 1b | 1c | 2 | 3 |
| 420A | 65.59 | 18 | 17 | 16 | 18 | 20 |
| 420B | 64.85 | 16 | 16 | 18 | 16 | 20 |
| 432 | 147.16 | 24 | 22 | 46 | 32 | 32 |
| 433 | 122.63 | 21 | 18 | 32 | 31 | 28 |
| 434 | 147.16 | 22 | 20 | 54 | 30 | 32 |
| 442A | 61.78 | 10 | 14 | 13 | 12 | 16 |
| 442B | 61.78 | 12 | 14 | 14 | 16 | 12 |
| 443A | 61.78 | 7 | 14 | 12 | 12 | 12 |
| 443B | 61.78 | 11 | 12 | 15 | 15 | 12 |
| 431A | 61.32 | 12 | 14 | 12 | 12 | 12 |
| 431B | 56.58 | 14 | 11 | 26 | 11 | 12 |
| SUM | 912.41 | 167 | 172 | 258 | 205 | 208 |

As observed in Table 1, a total of 11 modules from 7 different projects (e.g., project 420 consists of modules A and B) are addressed in the simulation model. A big discrepancy can be observed between the man-hour requirements of different modules due the high variability of projects attributes (number of openings, walls, etc.) thus producing an unbalanced production line with significant idle time between stations. In order to develop a stochastic model, the upper and lower ranges using a 95% confidence interval were estimated by applying student’s t-distribution. With these ranges and information in Table 1, the duration of tasks is modelled as triangular distributions and the simulation is run one thousand times, so its averages are collected and analysed.

Moreover, additional input data such as the hourly cost for fixed labour, multi-skilled labour, factory overhead, and the maximum number of workers allowed to work at the stations are displayed in Table 2. Since no multi-skilled labour is currently used on the production line, there is no evidence of its actual cost. Hence, the multi-skilled labour rate is assumed to be the same initially and, in subsequent simulations, possible additional labour costs (e.g., extra training, expertise, etc.) are addressed in increments of 20% to the hourly rate until it reaches double the fixed labour cost (i.e., $50/ hr). Factory overhead cost includes all stations depicted in Table 2 while the maximum number of workers to work in the multi-skilled stations is 7 due space constraints (i.e., not enough space for more workers to work in these stations). The results of the analysis are presented in the next section.

Table 2: Input data used in case study

| | |
|---|---|
| Cost for fixed labour | $25 /hr |
| Base cost for multi-skilled labour | $25 /hr |
| Increments for multi-skilled labour | Base cost + 20% |
| Factory overhead | $750/ hr |
| Max number of workers allowed | 7 workers |

## 4 MODEL VALIDATION & RESULTS

This section presents the results of the case study while providing insightful information regarding the impact of multi-skilled labour given the current factory layout. Initially, the simulation will run with the current factory state in which no multi-skilled labour is used. Results are then compared for model validation and alternative scenarios with the use of multi-skilled labour are simulated for further analysis. Finally, a scenario will be selected for further detailing and a schedule for multi-skilled workers will be developed based on simulation results.

For the validation process, the developed model simulated the production line under the same conditions as the model used by Moghadam (2013) to validate the productivity of the modular facility being studied. In this previous work, a simulation model was developed to validate the current production time (without multi-skilled labour) through comparing the model and actual production. The results of the developed model are compared with the previously validated model by the company and the results are 167.27 and 167 man-hours, respectively, with an error of less than 1%. Therefore, the developed model is validated through a comparison with previously validated models and actual results.

For the presentation of scenarios, the terminology for scenario names is SC 5-0 where the first and second number represent the number of fixed and multi-skilled labour used in the scenario, respectively. By adding multi-skilled workers and also using them to replace fixed labour, scenarios are developed respecting the maximum number of workers allowed in the stations as Figure 5 demonstrates the total time and cost of alternative scenarios against the current state (SC 5-0). As per Figure 5, all scenarios indicate reduction in both time and cost when using multi-skilled labour in the modular construction facility.

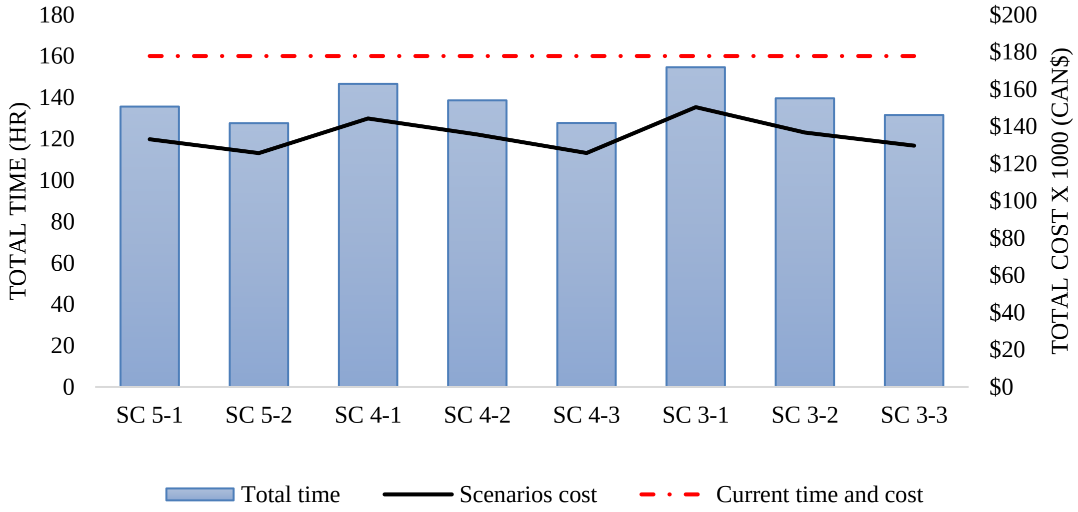


Figure 5: Total time and cost for addressed scenarios

Figure 5 demonstrates time and cost reduction through two strategies: (1) the use of multi-skilled labour in which no extra workers are added to the production line (SC 4-1,3-1 and 3-2) and (2) the addition of multi-skilled labour to the existing production line with the remainder of scenarios. Scenario 3-2 provides the best results when taking in consideration the impact of multi-skilled labour alone with a potential time and cost reduction of 21% and 23% respectively. These results indicate the impact of application of multi-skilled labour to balance the production despite its variability while introducing a new culture in the production line altogether.

However, the increase in the number of workers (fixed and multi-skilled) in the scenarios presents the lowest cost, which indicates that indirect cost (i.e., facility amenities, rental, administration, etc.) is a significant portion of overall cost. The lowest total time and cost are found in scenarios SC 5-2 and SC 4-3 where 2 additional multi-skilled workers are hired, and an extra multi-skilled worker could be trained from the original staff or could be a new hire as well.

In both cases, it is clear the initial stations in Figure 5 (1a,1b and 1c) are understaffed and, by following any of the presented strategies, more workers should be employed there. Moreover, the results indicate a shift in the production line's bottleneck from the Stations 1a,1b and 1c to Stations 2 and 3 in which further simulation should be applied to balance the production line as a whole. In order to do that more stations downstream should be modelled while identifying possible multi-skilled labour to be applied.

Furthermore, there is no clear evidence of the impact of an hourly rate increase, which is the premium for multi-skilled work; therefore, a more detailed analysis is required to better understand the true impact of multi-skilled labour on the overall cost of the production in the modular construction facility. Figure 6 demonstrates a sensitivity analysis of the scenarios with their respective number of fixed workers in each station, multi-skilled labour, total time, and the cost difference from the current baseline, which is SC 5-0 (5 fixed labourers only) as per Figure 6 and Equations 4, 5 and 6.

| SC # | Fixed labour | | | MS Labour | Total Time (hr) | Cost difference & rate increment for multi-skilled labour | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1a | 1b | 1c | | | +0% | +20% | +40% | +60% | +80 | +100% |
| SC 5-0 | 1 | 2 | 2 | 0 | 179 | 0% | 0% | 0% | 0% | 0% | 0% |
| SC 5-1 | 1 | 2 | 2 | 1 | 136 | -25% | -25% | -25% | -24% | -24% | -24% |
| SC 5-2 | 1 | 2 | 2 | 2 | 128 | -29% | -29% | -28% | -28% | -27% | -27% |
| SC 4-1 | 1 | 1 | 2 | 1 | 147 | -19% | -19% | -18% | -18% | -17% | -17% |
| SC 4-2 | 1 | 1 | 2 | 2 | 139 | -24% | -23% | -23% | -22% | -21% | -21% |
| SC 4-3 | 1 | 1 | 2 | 3 | 128 | -29% | -29% | -28% | -27% | -26% | -26% |
| SC 3-1 | 1 | 1 | 1 | 1 | 155 | -15% | -15% | -15% | -14% | -14% | -13% |
| SC 3-2 | 1 | 1 | 1 | 2 | 140 | -23% | -22% | -22% | -21% | -21% | -20% |
| SC 3-3 | 1 | 1 | 1 | 3 | 132 | -27% | -26% | -25% | -25% | -24% | -23% |

Figure 6: Sensitivity analysis of the scenarios

Figure 6 confirms the better results of scenarios SC 5-2 and SC 4-3 with a cost reduction of 29% for each, while indicating that premiums on multi-skilled labour do not contribute significantly to the overall cost in the production line: there is only a 3% increase in the total cost when multi-skilled labourers earn twice as much as fixed labour workers. However, it is important to note the developed simulation addresses the production at its natural state and it does not simulate the impact of these changes during implementation stages. Hence, it is reasonable to forecast an additional cost due to the implementation of changes and adaptation of workers to new environment and workflow. Moreover, both scenarios indicate a reduction of 29% in comparison to the current production time (SC 5-0), the scenario against which all comparisons are being performed. Another remaining question is the impact of direct and indirect cost when addressing the use of multi-skilled labour in modular construction facilities. In order to do that, a scenario will be chosen for further analysis.

Although results from both scenarios SC 5-2 and SC 4-3 are similar, the first scenario of those scenarios is chosen for further analysis since it provides less change in the current state of the production line (i.e., re-training currently employed labourers wouldn't be necessary, which means the modular contractor can hire 2 additional multi-skilled workers). Figure 7 shows the cost breakdown between direct and indirect costs represented by the work in stations and factory overhead, respectively, while the chart on the right describes the cost contribution between fixed and multi-skilled labour for the stations being considered in this case study.

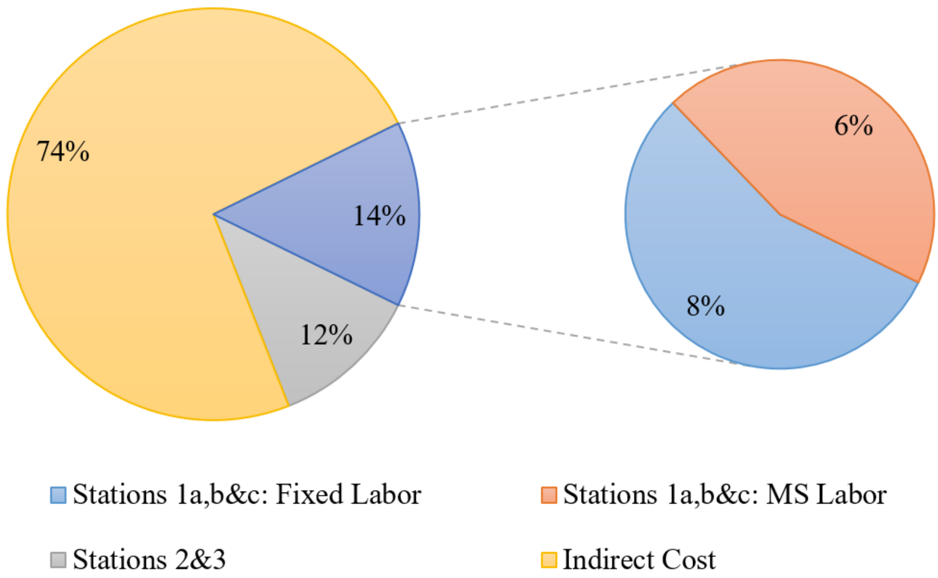


Figure 7: Cost breakdown of Scenario 5-2

As shown in Figure 7, the less favourable scenario in which multi-skilled labourers are paid twice as much as fixed labourers is taken into consideration in order to provide the modular contractor a broader insight into the difficulties of involving multi-skilled labour in its production line. From the graph, it is clear the indirect cost is the highest contributor, representing almost two thirds of the overall production cost. Even considering the worst case, in which the hourly rate premium for multi-skilled labour is at the highest amount considered in this study, the use of multi-skilled labour only impacted the overall cost by 6%, where, when the multi-skilled rate is the same as the rate for fixed labour, the impact is reduced to as low as 3%.

Considering the cost reduction of 29% between the current production cost and the evaluated scenario (SC 5-0 and SC 5-2, respectively), it is safe to recommend the use of multi-skilled labour in the modular construction facility. Moreover, Figure 7 indicates that in order to significantly reduce the overall cost, future improvement should be focused on reducing overall production time in order to minimize indirect cost that represents the factory's overhead (functioning hourly cost). To finalize the proposed work, a schedule for the proposed multi-skilled labour suggested in SC 5-2 is developed based on simulation results and the needs for multi-skilled workers at the stations as per Equation 1.

Figure 8 shows the schedule for SC 5-2 in which two multi-skilled labourers assist the respective stations in the plant for each 4-hour shift needed to complete the 11 simulated modules. This schedule was developed assuming 5 fixed labourers and assuming that the multi-skilled labourers are able to work freely between the floor, wall and roof stations. The schedule highlights the need for dynamic labour to balance the production lines. As variability in projects is encountered, the production rate of the lines shifts to accommodate this.

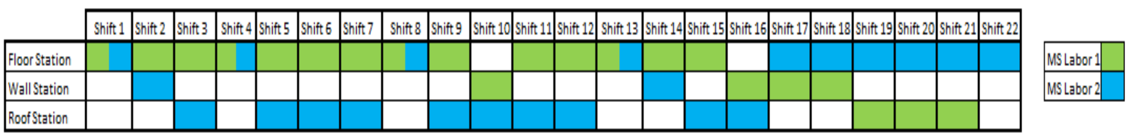


Figure 8: Proposed multi-skilled labour schedule for Scenario 5-2

## 5 Conclusions

The research intends to explore the interactions between discrete and continuous simulation thus proposing a hybrid approach to address the impact of multi-skilled worker in modular construction facilities using simulation while addressing the context of each production line and its limitations. Through the development and validation of a hybrid simulation, several scenarios were developed taking into consideration the maximum number of workers allowed due to space constraints, direct cost, multi-skilled work premiums and indirect cost such as factory's overhead. The hybrid approach is demonstrated to be effective in simulating the variable duration of construction task as per the availability of multi-skilled labourers through work shifts and overall production's balance.

Moreover, 11 modules from 7 different projects were simulated taking into consideration each module's attributes and variability. According to simulation results, the impact of multi-skilled labour is positively confirmed with a time and cost potential reduction of 21 and 23%, respectively while not adding extra labour to the production line and relying on the levelling of resources entirely.

However, and despite what many people often assume, the addition of more workers contributes to a decrease in the overall cost and production time. It was shown here that adding 2 multi-skilled workers to work in 3 different stations as per required at the end of each work shift reduces the total production time by 29% when compared with the current production time, which uses 5 fixed labourers who only work at their respective stations.

Moreover, it is concluded that by adding 2 multi-skilled workers to the production line the overall cost is reduced by 29%, while the cost attributable to multi-skilled labour only represents 6% of the total. In fact, the main contributor for the overall cost is the indirect cost, which is responsible for almost 75% of the total thus suggesting the modular contractor develop other solutions to reduce total production time and cost.

After the trade-off analysis is performed and suitable scenarios are selected, a schedule for the multi-skilled labourers is developed in order to provide better scheduling for floor managers regarding where to allocate labour resources. The information from the schedule is extracted from the simulation model and later modified to fit the manager's preference following the shift's duration at the modular facility.

Finally, in order to identify the impact of multi-skilled labour in a general problem, this research suggests the following steps to evaluate the impact of multi-skilled labour in operations:

1. Observe the process in question,
2. Analyse the process using metrics at hand (e.g. time, cost, etc.),
3. Identify which work (in this case, stations) in the process can be improved by the use of multi-skilled labour,
4. Simulate the current and proposed scenarios,
5. Analyse the different scenarios as per metrics used in Step 2.

Although this study provides interesting insights in regards to the use of multi-skilled labour in modular construction facilities, the simulation model still has certain assumptions limiting its capacity such as: (1) adequate space to store idle panels between stations, (2) fixed and multi-skilled labourers have the same productivity rates. Moreover, this work does not consider the implementation and adaptation process of introducing the multi-skilled labour in the production line, nor integrated new projects attributes in a systematic manner for further analysis. A hybrid approach is further considered to simulate other aspects of production such as the learning effect on multi-skilled labourers and employee turnover. Hence, the authors intent to explore and address these assumptions in future research.

## 6 ACKNOWLEDGEMENTS

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