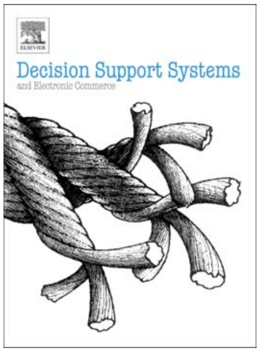

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PII: S0167-9236(13)00180-2
DOI: doi: 10.1016/j.dss.2013.06.009
Reference: DECSUP 12367

To appear in: *Decision Support Systems*

Received date: 23 December 2011
Revised date: 28 January 2013
Accepted date: 13 June 2013

Please cite this article as: Wim Laurier, Geert Poels, Invariant Conditions in Value System Simulation Models, *Decision Support Systems* (2013), doi: 10.1016/j.dss.2013.06.009

Invariant Conditions in Value System Simulation Models

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Abstract: This paper presents a framework for the integration of supply chain (or logistics/distribution), value chain (or financial), and business process (or operational/manufacturing) simulation models, which should facilitate assessing the impact of supply chain and operational changes on an enterprise's financial performance. A Design Science approach is taken to demonstrate that the REA ontology, which provides a shared conceptual ground for these three model types, and its axioms, which describe invariant conditions for value systems, can help to build conceptually sound simulation models and identify the integration points between these models. It is further shown how these three types of simulation models can be integrated into one value system model for discrete event simulation, making use of the ExSpecT simulation tool. With this ontology-based framework, simulation model builders should be able to scope their models better and define integration points with other models, which is expected to promote the (re)use of simulation models for different purposes (e.g., simulating logistical, operational and financial performance).

Keywords: value system; supply chain; value chain; business process; resource-event-agent ontology, integration, virtual organization

1. Introduction

Information technology is important for acquiring competitive advantage in dynamic business environments [1]. When the cost of error is high, information technology provides practitioners with the information that is needed to develop conceptual models that provide a true and fair view of a future reality. These conceptual models are then used to simulate and analyze the predicted behavior of the future reality. For example, before an airplane prototype makes its maiden trip many simulation models have been made to study the predicted behavior of individual airplane parts and the plane as a whole. These simulation models support technology advances, while saving money and lives. Church and Smith [2] advocate and demonstrate the use of simulation models for managerial decisions, potentially saving money and jobs. Where most current approaches limit themselves to the simulation of logistical and manufacturing processes, considering only logistical and operational parameters such as production cost, service time, product quality and process flexibility [3-5], Church and Smith stress that business performance is mainly evaluated in terms of financial parameters (e.g., profit, net present value). Consequently, not only logistical and operational parameters such as operational cost but also financial parameters such as cost of capital should be taken into account when building simulation models for evaluating the future performance of alternative business process and supply chain designs. Integrating financial parameters in supply chain simulation models can help overcome financial sub-optimization[1] caused by the optimization of logistical and operational parameters without the assessment of their impact on financial parameters, as it allows for simultaneous optimization of operational performance and profitability [7].

Creating conceptual models for simulating business process, enterprise and supply chain performance is a challenging task, especially because – in practice – businesses form a small part of a much larger economic environment. As a result, conceptual models for the purpose of simulating business processes, enterprises and supply chains cannot be considered standalone artifacts, since *“today’s highly complex systems require that simulation models developed by different teams in*

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[1] Sub-optimization: Independently optimizing the sub-systems of a given system will in general not optimize the performance of the system as a whole. 6.Machol, R.E., W.P. Tanner, and S.N. Alexander, *System engineering handbook*. 1965, New York,: McGraw-Hill.

different domains interact with one another to serve a higher goal." [8] The simulation models developed by specialists with different domain expertise are often called *federates*, the aggregated simulation model that consists of interacting federates is often called a *federation*, and the approach is called *component-based simulation* [8]. The main challenge of component-based simulation is assembling federates, which may not have been developed with federations in mind, while preserving syntactical and semantic correctness [8].

The management of a virtual organization[2] is a typical situation in which the cost of error is high (i.e. the failure of one partner might cause the whole virtual organization to fail) while financial, manufacturing and distribution processes have to be managed simultaneously because of their interdependence [9]. Many authors look at supply chain simulation models [5, 10, 11] or business process simulation models [2] as isolated artifacts. They build standalone simulation models, limiting the scope of their models to the supply chain, abstracting from the internal business processes of each supply chain partner, or limiting the scope to individual business processes, abstracting from the value and supply chain in which they are embedded. Other approaches that do map supply chain models with business process models only focus on operational evaluation criteria [5, 12]. These operational approaches are prone to sub-optimization, since improved operational performance does not automatically lead to better financial performance [13]. A challenge of virtual enterprises is that operational and logistic processes have to be integrated across enterprise boundaries and financial performance is evaluated at the level of the individual supply chain partners (i.e. virtual enterprise components). Component-based simulation should be able to mitigate this challenge.

Although integration frameworks and methods exist, none of them integrates all dimensions needed for virtual enterprise management. For example, the Supply-Chain Operations Reference model (SCOR) [14] provides a framework for integrating operational and logistic processes but does not explicitly address the financial performance of individual supply chain partners. Where the e3-

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[2] A virtual organization is a synergetic alliance between separate firms that join their best-of-breed value-added activities (i.e. core-competencies) to take advantage of a market opportunity. 9. Strader, T.J., F.-R. Lin, and M.J. Shaw, *Information infrastructure for electronic virtual organization management.* Decision Support Systems, 1998. **23**(1): p. 75-94.

value ontology[3] [17] integrates financial and distribution processes, its conceptualization of manufacturing processes is too coarse grained for operational simulation models. Where Dietz' enterprise ontology [18] provides an excellent theory for modeling processes across enterprise boundaries, it explicitly renounces the existence of an "exchange layer" in which one actor gives something in return for something given by another actor [19]. This "exchange layer" is essential for components of a virtual enterprise as they need to be able to assess their own profitability as part of a virtual enterprise [20].

What is needed is a framework that is able to integrate simulation models for assessing the financial, operational and logistical performance of enterprises, the supply chains in which these enterprises are embedded and the business processes embedded in each enterprise. The framework should allow us to assess relevant performance parameters using individual simulation models (e.g. one business process or one enterprise in isolation), using simulation models as part of a federation of models (e.g. a business process as part of an enterprise that is part of a supply chain) and using a simulation model as a federation of lower-level models (e.g. a supply chain composed of several enterprises, which have their own business processes). The federation level is required to assess the performance of the entire virtual organization, as the business processes of the firms of which the virtual organization is composed need to operate as a single business process, while each participating firm needs to be profitable at the same time. In the remainder of this paper, this federation of simulation models will be called the *value system* simulation model. The abstraction levels identified within this value system simulation model will be referred to as *supply chain* (i.e. the level at which individual enterprises communicate and trade), *value chain* (i.e. the level at which individual enterprises or organizations balance logistic flows with mirroring money flows) and *business process*

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[3] Like modeling frameworks, ontologies can be used to represent structured and semi-structured information about a domain. For example, the constructs and axioms, which are defined as fundamental truths about a domain for which there is no counterexample or exception, of an ontology can be used to develop a domain-specific modeling language that can constrains modelers to develop case models that are a true and fair view of the domain. 15. Gailly, F., W. Laurier, and G. Poels, *Positioning and Formalizing the REA enterprise ontology*. Journal of Information Systems, 2008. **22**(2): p. 219-248, 16. Bahrami, A., *Object oriented systems development*. 1999, Boston, Mass. ; London: Irwin/McGraw-Hill. 411 p.

(i.e. the individual processes that use information to orchestrate logistic, operational and financial flows and produce information while orchestrating).

Since the REA ontology [21] is – to the best of our knowledge – the only ontology that supports the modeling of individual business transactions and financial, distribution and manufacturing processes and supply chains, its level of abstraction is considered appropriate for providing the framework for the integration of federates. This paper demonstrates how the REA ontology can be used to create value system simulation models. The REA ontology describes enterprise economic phenomena using resources, agents and events as primitives and describing the necessary associations between these primitives with three axioms [22]. These axioms phrase fundamental truths for which there are no counterexamples or exceptions within the enterprise economic domain [16], which includes supply chains, value chains and business processes. Consequently, they represent invariant conditions that apply to the simulation model federates and federation (i.e. value system) introduced above, which is key to the integration solution presented below.

The following section addresses the research methodology employed for realizing our purpose. The third section discusses related work, and provides background on the REA ontology and discrete event simulation with Petri-nets. Section four rephrases the REA axioms at each value system abstraction level (i.e. supply chain, value chain, business process), to emphasize the integration points between the abstraction levels. In section five a value system simulation model that integrates the supply chain, value chain levels, and business process levels for an exemplar virtual organization (i.e., the Beer Game [23]) is built, and example simulation runs using the model are presented and used to illustrate the benefits of our REA ontology-based value system simulation modeling approach. Conclusions and directions for future research are given in the last section.

2. Research methodology

The research method applied in this paper is inspired by design science [24, 25]. As opposed to behavioral science, which limits itself to developing and verifying theories that explain or predict human or organizational behavior, design science seeks to extend the boundaries of human or organizational capabilities by creating new and innovative artifacts. Unlike routine design, which applies existing knowledge to solve problems, design science research addresses previously unsolved problems in unique or innovative ways. Problems typically addressed by design science are characterized by (1) unstable requirements and constraints based on ill-defined environmental contexts, (2) complex interactions among subcomponents of the problem and its solution, (3) inherent flexibility to change design processes as well as design artifacts, (4) a critical dependence upon human cognitive (e.g., creativity) and social (e.g., teamwork) abilities to produce effective solutions [24].

When designing value system simulation models, all these problem features can be recognized. *"The supply chain environment is dynamic, information intensive, geographically dispersed, and heterogeneous."* [26] The dynamism of the supply chain environment is inextricably bound with the unstable requirements and constraints in the simulation model articulation process. This dynamism also motivates the need for inherent flexibility to change the design process and artifacts (e.g., when existing approaches or models prove to generate unsatisfactory results due to new environmental conditions). Together with the dynamism, the information intensive character of the supply chain environment provokes ill-defined environmental contexts as it would be impossible or at least unreasonably costly to gather all relevant information. The geographic distribution of supply chain partners, which adds unpredictable transportation times due to traffic, different work conditions and legislation to the list of variables, interacts with other subcomponents of the problem and solution (e.g., the financial soundness of trading partners, business process, workplace and supply chain lay-out). Finally, the heterogeneity of the supply chain environment and the jargon for each (sub-) discipline challenge human social and cognitive abilities to communicate their knowledge to supply chain partners and understand the information supply chain partners provide.

The design science approach provides researchers with guidelines for extending the boundaries of human or organizational capabilities by creating new and innovative artifacts [24]. These guidelines intend to assure the quality of problem solving research, like methodological requirements are expected to assure the quality of research in established research disciplines (e.g., behavioral research, natural science). However, since design science aims at providing generic quality assurance guidelines for new research disciplines that did not develop their own rigorous research methodologies yet, these guidelines are not as restrictive as methodological requirements in established research disciplines are.

Design science requires that a purposeful artifact is created that addresses an important organizational problem [24]. The artifact must also be described effectively, enabling its implementation and application in an appropriate domain. The problem addressed in our research is the reconciliation of financial, logistical and operational parameters and performance criteria in business process, enterprise, and supply chain simulation models. The purposeful artifact that is described in section five of this paper is an REA ontology-based discrete-event simulation[4] model of the Beer Game [23] value system. Although the example described in section five is fictitious, it is well known as a business game for studying the behavior of complex systems [23] and it is representative for the research problem addressed by the paper. To strengthen ecological validity, the example value system simulation model is created with the Petri-nets-based ExSpecT tool that was developed by Deloitte [28], who have used it in their consulting practice to implement discrete event simulation models for analyzing operational and logistical business performance [29].

Design science also requires that appropriate methods are used to construct (i.e., to make sure the artifact satisfies the laws in the problem environment) and evaluate the artifact [24]. Construction rigor was achieved by using the REA ontology concepts and axioms as a framework for the simulation model design process. To achieve this construction rigor, the REA axioms had to be analyzed and rephrased at the level of supply chain, value chain and business process. This analysis, which is presented in section four, is the main scientific contribution of this paper as it provides a foundation for the design of value system simulation models that allow assessing operational, logistical and financial performance variables at supply chain, value chain and business process levels. Evaluation rigor was achieved by running predictable simulations on the Beer Game value

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[4] Discrete event simulation addresses the behavior of discrete event systems, in which phenomena of interest can only change state or value at discrete moments of time rather than continuously with time. For example, the number of passengers can only change when a bus arrives at a stop. 27. Fishman, G.S., *Principles of discrete event simulation*. Wiley series on systems engineering and analysis. 1978, New York: Wiley. xviii, 514 p.

system simulation model and checking whether the outcomes matched the expected simulation outcomes.

3. Simulation Model Design: Related Work and Background

This section first discusses related work on the use of ontologies as design frameworks for simulation models. Next, it presents the REA ontology that provides the key element, in the form of a set of invariant conditions originating in ontology axioms, for integrating supply chain, value chain and business process simulation models. Finally, it describes the Petri-net-based ExSpecT tool that was used to articulate and execute the value system simulation model constructed with our REA-ontology-based approach for the Beer Game.

3.1. Related Work

Domain ontologies are frequently used to overcome the challenges imposed by the dynamism, heterogeneity and information intensiveness of the supply chain environment. Since domain ontologies provide a formal or at least explicit specification of a conceptualization that is shared by multiple contributors [30, 31], they can help overcome (e.g., by providing a shared vocabulary and list of model constraints and requirements) the cognitive and social challenges that find their origin in the heterogeneity of the supply chain environment. These features also make domain ontologies useful for explaining, interpreting and integrating simulation models. As domain ontologies also represent the invariant conditions of the domain of interest (e.g. enterprise economic phenomena) [32], they can also help discriminate the evolution mechanisms in the dynamic supply chain environment.

Many other authors have already advocated the use of ontologies in various facets of value system modeling for simulation purposes (e.g., supply chain simulation models). For example, the e3-value ontology [17] was especially developed to evaluate the profitability of e-business models (i.e., value chain designs) and the supply chains, or more appropriately the value nets as e3-value does not assume stable, long-term relationships between partners, they participate in. Later, the e3-value ontology's scope was extended towards generic business models, including non-profit organizations (.e.g., healthcare [33]), and the application domain was widened towards different kinds of strategic management (e.g., control [34]) and strategic analyses (e.g., risk assessment [35]). However, the e3-value ontology does not support the representation of individual business processes and transactions, which are explicitly considered outside the ontology's scope [17].

Also other ontologies look at business from a strategic perspective that abstracts from the logic of individual business transactions (e.g., business modeling ontology (BMO) [36], business motivation model (BMM) [37], Ushold's [38] enterprise ontology). Since these ontologies abstract from business processes and individual business transactions, they cannot be used as a framework for the integration of the discrete-event simulation federates discussed in the introduction, which simulate and analyze financial, distribution and manufacturing processes at the level of individual operations, into a value system federation.

Moreover, domain ontologies have been presented as the silver bullet for simulation model integration and reuse, which is expected to reduce redundant modeling effort (e.g., by reusing a manufacturing process model, integrating it in a supply chain model to show its effect on the performance of the entire supply chain) [8, 39]. Fayez et al. [26] develop a supply chain ontology for simulation model annotation that is based on the supply chain operations reference model (SCOR) [14]. Dong et al. [12] then develop a SCOR-based simulation tool that supports the integration of supply chain and business process models for operational simulation models, which abstract from financial parameters. Cope et al. [40] then demonstrate that using ontologies as a knowledge base for simulation model development significantly reduces the time that is required to develop a supply chain simulation model.

Although this review of related work makes clear that the REA ontology is not the only ontology to describe business or enterprise, it is – to the best of our knowledge – the most appropriate ontology to integrate operational and logistical information with financial information, as it was originally developed to create a "shared data environment" for accountants and non-accountants [41]. The REA ontology finds its origin in accounting [41] and has been defined at the level of supply chains [42], integrating financial and logistic flows between trading partners, value chains [43, 44], integrating financial and logistic flows within each trading partner, and business processes [45, 46], capturing the essence of the financial, distribution and manufacturing processes of each trading partner.

3.2. The REA Ontology

The REA ontology was introduced by W.E. McCarthy as a data model for a generalized accounting framework in a shared data environment in which both accountants and non-accountants (e.g., managers, salespeople) are interested in maintaining information about the same phenomena in the enterprise [41]. This data model originates in a modeling method that aimed at integrating database technology and accounting theory [47].

Economic resources represent the goods, services, rights and money that are produced (and stocked) by and flow through enterprises. *Economic events* represent the occurrences in time that animate these enterprises and drive those resource flows. *Economic agents* are the natural and legal persons (e.g., trading partners) that participate in those events (e.g., as executor). Since REA finds its origin in accounting it advocates the use of a particular association between economic events (i.e., duality), in addition to the flow of stocks (i.e., economic resources) and the participation of economic agents in economic events. Duality relates increment events – which represent a stock increase – to decrement events – which represent a stock decrease – representing the economic rationale, which requires that all resources an enterprise gives up (e.g., by shipping them to a customer) should be replaced by resources of equal or greater value (e.g., through a cash receipt).

Later, the constructs from the data model were augmented with axioms to create the actual REA ontology [48, 49]. These axioms addressed the rules that govern business seen from the perspective of a single trading partner. The first REA axiom stipulates that *at least one inflow event and outflow event exist for each economic resource and that inflow and outflow events must affect identifiable resources*. [48] Consequently, this axiom requires that every economic resource has its origin in an inflow (i.e., increment) event and a purpose (i.e., being used in an outflow/decrement event). The second REA axiom addresses the economic rationale by requiring that *all events effecting an outflow must be eventually paired in duality relationships with events effecting an inflow and vice versa*. [48] Together, these two axioms define a healthy metabolism for an enterprise. The first axiom requires that all resources are useful and no resources will be stored perpetually. The second axiom requires that the enterprise is rewarded for its efforts, preventing that its resources drain away. The third REA axiom then specifies that *each exchange needs an instance of both the inside and outside subsets* [48], requiring that each business transaction involves at least two trading partners (i.e., the enterprise that defines the viewpoint and an outside agent (e.g., supplier, customer)). Additionally, this axiom specifies that there is always an agent inside the enterprise (e.g., a sales person) accountable for the transaction.

Most recently, REA's trading-partner view (i.e., from the perspective of one party in a business transaction), which addresses value chains and business processes, on the economic reality was complemented with an independent view, which focuses on the interactions between trading partners from the perspective of an independent observer that is not taking part in the business transactions. This independent view was developed for the purpose of developing an ISO standard for open-edi (i.e., electronic data interchange) that is specific for business transactions [42], and is particularly useful for describing supply chains and other kinds of business collaborations. Although this standard takes a perspective on business that is totally new to REA, the REA primitives and axioms are also applicable in this context, since the same business reality is described and only the perspective has changed. Even in the independent view, resources need to have an origin and a purpose, enterprises need to benefit from their activities, business transactions involve at least two trading partners and people are accountable for business transactions. Hence, REA's axioms describe the invariant conditions that apply to business processes, supply and value chains.

3.3. Petri-net theory and discrete event simulation

The Executable Specification Tool (ExSpecT) [50] was selected for the specification of the discrete-event simulation models in this paper, because of its full-graphic user-interface and sound formal basis in Petri-net theory. The tool was specifically developed to predict the operational performance of alternative business process lay-outs by simulating workloads, goods and information flows [28].

Petri-nets are one of the many ways to perform discrete event simulation, but they have gained considerable weight in the workflow and business process domain. They combine sound mathematical foundations with intuitive visualizations. Therefore we have considered them to be most appropriate for demonstrating the integration of supply chain, value chain and business process simulation models in this paper. The ExSpecT tool incorporates features of colored, timed and hierarchical Petri-nets. These different types of Petri-nets add specific features to conventional Petri-nets.

Conventional Petri-nets consist of four elements (i.e., tokens, places, arcs and transitions) [51]. *Tokens* represent things that have an identity and flow through a modeled process (e.g., a package through a logistic process). They are often represented as dots. *Places* store tokens and are often represented as circles that can contain dots, which represent tokens. *Transitions* represent events; processing tokens by moving them form one place to another. Transitions are often represented by boxes or rectangles. Finally, *arcs* indicate which transitions are allowed to consume tokens from a place (i.e., input arc) and which places can receive a token from a transition (i.e., output arc). When a transition consumes a token from one or more places, which are called its input places, and one or more places, which are called its output places, receive a token from this transition, this transition is said to fire. In the original Petri-net notation, a transition is only allowed to fire when all of its input places, which are connected with this transition through an input arc; contain a token. When the transition fires; all of its output places, which are connected with this transition through an output arc, receive a token. Where the transitions in the original Petri-nets represent AND-port semantics, firing when all their input places contain at least one token and placing a token in each of their output places, alternative Petri-net based notations may define OR-port semantics that allow a transition to fire when only one of its input places contain a token and depositing a token in only one of its output places. Even NOT-port semantics can be defined, requiring that a certain transition can only fire when its input place contains no token.

Colored Petri-nets are Petri-nets that allow tokens to have data values. The color of a colored Petri-net token is a metaphor for its data value. In colored Petri-nets, it is possible to define transitions that can only fire when the precondition that one or more of its input ports contain a token of a certain color (i.e., with a particular data value) is fulfilled. Transitions in colored Petri-nets can optionally change the color (i.e., data value) of the tokens they process (e.g., merging, splitting or modifying the data they receive from the tokens they consume). Timed Petri-nets are Petri-nets that keep track of time, allow transitions to have a duration incorporating the possibility to delay the processing of tokens. Hierarchical Petri-nets then allow the specification of transitions in a higher-level Petri-net as an entire lower-level Petri-net, which allows for the decomposition of complex Petri-nets in a layered constellation of more homogeneous partial Petri-nets (e.g. a federation of federates) [52].

The Petri-net based ExSpecT executable modeling and simulation language defines *processors*, which are the equivalent of transitions, as active objects in a network and *channels*, which are the equivalent of places, as passive elements of a network, which is a discrete-event simulation model. Depending on the kind of channels that contain them, tokens may represent units of information, control or physical objects. These tokens can have data values, which conforms to the features of a colored Petri-net. *Stores* are a specific kind of channel that contains a single token, which usually stores the result of a data operation as the data value of that token, at all times. If the tokens in the input channels of a processor satisfy certain preconditions, the processor may be activated. These preconditions can be specified by the modeler. Upon activation, the activating tokens, which satisfy the precondition, are consumed. The production of the processor’s output channels then may be subject to delay, which is typical for timed Petri-nets. In the ExSpecT language, a certain set of processors and channels can be grouped together in a separate subnet or *system*, which can be (re)used to build larger systems by connecting *pins* (i.e., a kind of channels especially designed to allow for model (de)composition as in hierarchical Petri-nets) within the subsystem to the channels of the larger system. [28]

4. Framework presentation: Rephrasing the REA axioms for value systems

In this section, we analyze the REA axioms and rephrase them at the level of abstraction appropriate for supply chains, value chains and business processes. Although the REA ontology has been applied at all levels of abstraction, the original REA axioms [22] take the perspective of a single enterprise only. As a result, the integration between the levels of abstraction is only implicitly present.

To highlight the differences and integration points between these levels of abstraction, the original REA axioms are decomposed into rephrased REA axioms for the supply chain, value chain and business process levels. The rephrased axioms are summarized at the end of this section in table 1.

4.1. The Invariant Conditions in Supply Chain Models

Supply chain models are the top layer federates in the hierarchy of our simulation model federation. For the construction of these models, we refer to the REA ontology as it is specified in ISO's Open-edi Business Transaction Ontology (OeBTO) [42]. These top-layer models show organizations, which are a sub-type of REA's economic agent construct and are defined as '*a unique framework of authority within which a person or persons act, or are designated to act, towards some purpose*'. [42] These organizations represent trading partners, which play the seller and buyer role in supply chains.

The supply chain level only contains the information and resource flows regarding exchanges between trading partners. At this level the first REA axiom implies that each resource flow has a source and a sink. The source is the outflow event for the organization that gives the resource away. The sink is the inflow event for the organization that takes up the resource that was given away. In both situations the three REA primitives are linked to each other: an event (i.e. inflow or outflow) affects a resource from the viewpoint of an organization (i.e. give or take). Consequently, the first REA axiom has been rephrased as *resources have to flow from one organization to another* at the supply chain level. An organization's resource outflows typically find their origin in its resource inflows, which is imposed by the second REA axiom at the business process level.

The 'outside subset' constraint imposed by the third REA axiom then describes the construction of supply chains, requiring that every exchange requires at least two trading partners. This REA axiom has been rephrased as *each exchange requires at least two trading partners*. The construct that involves two or more trading partners to do business is called a "collaboration space" in the OeBTO standard. The resource flows of an exchange typically have opposite directions, which is imposed by the second REA axiom, at the value chain level. Since the second REA axiom at the supply chain level is enforced by the application of the rephrased second axiom at the business process and value chain level, it is not rephrased at the supply chain level to avoid redundancy. Besides, it should still be possible to consider purely logistical models as conceptually sound when the value chains level, which contains the economic rationale, is not required.

4.2. The Invariant Conditions in Value Chain Models

Value chain models link supply chain and business process models to each other, shaping the middle layer of our model hierarchy. They are based on the REA ontology as it is specified in [43]. This middle layer shows the entrepreneur script, which describes how trading partners engage in value-added exchanges. This entrepreneur script contains three major parts (i.e., acquisition, revenue and conversion cycle) and an auxiliary part (i.e., financing cycle). The *acquisition cycle* represents how the individual trading partner purchases materials and labor from its suppliers (e.g., material vendors, employees) usually in return for money. The acquisition cycle is similar to the SCOR [14] source process, which also relates the operational processes that acquire products with the payments that remunerate them. The *conversion cycle* shows how labor and raw materials are converted into finished goods inside the trading partner's organization. The conversion cycle incorporates the entire SCOR make process. The *revenue cycle* represents how the individual trading partner sells finished goods to its customers, usually in return for money. [44] The revenue cycle intersects with the SCOR deliver process, which makes sure delivered products generate return. The auxiliary financing cycle then supplies the acquisition cycle with money by acquiring money through the revenue cycle or from creditors (e.g., banks, shareholders). This financing cycle is a main difference between the SCOR reference model for supply chains and the REA ontology because the financing cycle is not explicitly addressed in SCOR due to its operational focus.

In value chain models, the first REA axiom has to be satisfied by ensuring that every resource in- and outflow that affects the organization at the supply chain level, relates to a resource that is known at the level of the organization's business processes. Consequently, this axiom defines the integration points between the supply chain and the business process level at the level of value chains.

The second REA axiom has to be satisfied within the context of each cycle (i.e. acquisition, conversion, revenue, financing). Within the acquisition cycle context, a resource inflow (typically a product or service acquisition) has to be eventually paired in duality with a resource outflow (typically a payment), to settle a purchase. Within the context of the revenue cycle, a resource outflow (typically a product or service delivery) has to be paired in duality with a resource inflow (typically getting paid), to settle a sale. The acquisition and revenue cycle represent the opposing views of trading partners involved in the same exchange. Consequently, the second REA axiom, which has been rephrased as *each organization involved in an exchange has to give up resources to take up other resources*, helps to define fair exchanges. The conversion and financing cycle are governed by the business process articulation of the second REA axiom, which will be discussed in the next sub-section.

The third REA axiom requires that an exchange involves a trading partner (i.e. "an instance of the outside subset") and a person (i.e. "an instance of the inside subset") responsible for the business process that executes the exchange. The trading partners are modeled at the supply chain level and the responsible persons are modeled at the business process level. As a result, the value chain level does not have a rephrased version of the third REA axiom.

4.3. Business Process Models

The business process models provide the bottom layer of our model hierarchy and use the REA ontology as applied in [45, 46]. This layer shows business processes as they are usually represented (i.e., with a particular purpose and as part of a larger organization). These business processes consist of economic events and business events. As for the value chain level, *economic events* are events in which organizations gain or lose control over economic resources (i.e., ownership of a resource or the ability to derive economic benefit from a resource). Business events, on the other hand, are the workflow tasks that organizations wish to monitor and control and need to be accomplished to complete a business process. As *business events* occur, they cause a business process to move through various phases of planning, actualization and post-actualization [42].

At the business process level, the first REA axiom demands that each resource has an origin (i.e. an inflow) and is used for some purpose (i.e. an outflow). Consequently, resources cannot be stocked eternally inside organizations. The axiom also specifies that economic events must produce resources (i.e. inflow) or consume resources (i.e. outflow). Consequently, events that do not produce or consume resources are not economic events. They are business events. At the business process level, the second REA axiom represents the law of conservation of matter, requiring that an event that consumes resources must produce resources and vice versa. Together with the first, the second REA axiom describes the chain of events of which a business process is composed. Within the conversion cycle, business processes can be composed of several events. For example, raw materials are acquired (i.e. inflow), they are used (i.e. outflow) to produce (i.e. inflow) a semi-manufactured product. This semi-manufactured product is then used (i.e. outflow) to produce (i.e. inflow) a final product, which is then sold (i.e. outflow). Within the financing cycle we observe the same logic: money is borrowed from the bank or received from customers (i.e. inflow), later it is used to pay suppliers or reimburse the bank (i.e. outflow). Meanwhile it can be wired from (i.e. outflow) one internal account to (i.e. inflow) another.

Since the second part of the third REA axiom is specific for the supply chain, only the first part is relevant for the business process level. Also this part should better be rephrased as *at least one member of the organization should be responsible for each economic event.*

Table 1. Modeling guidelines as incorporated in the REA ontology axioms

	1st REA Axiom	**2nd REA Axiom**	**3rd REA Axiom**
Supply Chain	*Resources have to flow from one organization to another*		*each exchange requires at least two organizations*
Value Chain	*Inflow and outflow events must affect identifiable resources.*	*each organization involved in an exchange has to give up resources to take up other resources*	
Business Process	*at least one inflow event and outflow event exist for each economic resource and that inflow and outflow events must affect identifiable resources*	*all events consuming a resource must eventually produce a resource and vice versa*	*at least one member of the organization should be responsible for each economic event*

5. Framework demonstration: Building Value System Model for the Beer Game

In this section, a discrete-event simulation model for the “Beer Game” [23] is built and discussed, to demonstrate the benefits of using the REA ontology as a framework for developing discrete-event simulation models for value systems. The beer game scenario is used instead of a real case study to be able to show the benefits of the modeling approach without having to obtain permission of all supply chain partners involved. The beer game also has the advantage that the expected behavior of the value system is well documented. As a result, we were able to evaluate the true and fair representation of the value system’s behavior by running simulations according to the beer game scenario.

The “Beer Game” or “Beer Distribution Game” was developed as an introduction to the fundamentals of the behavior of complex systems in which people play key roles. While playing the game, participants experience the pressure of playing a role in a complex system like a supply chain. The participants discover that a supply chain’s structure produces its behavior, but also that its behavior is greatly influenced by their decisions.

5.1. Supply Chain Model

In the supply chain model, ExSpecT systems represent the organizations that play the seller and buyer role. ExSpecT channels represent the resource and information flows they exchange. The organizations’ value chains are represented as subnets of the ExSpecT systems. However, these value chains are optional at this level of abstraction. For example, in figure 1 the RETAILER, WHOLESALER and DISTRIBUTOR ExSpect systems contain value chain models, where CUSTOMER 2 has been modeled representing only his properties in the system (i.e. orders 1 beer a day and pays on time). Consequently, supply chain models are allowed to contain a mix of elaborated and rudimentary organization models. The CUSTOMER and FACTORY ExSpecT system only contain partial value chain models (i.e. the CUSTOMER does not contain a revenue cycle, the FACTORY does not contain an acquisition cycle) as they are located at the boundaries of the supply chain.

Figure 1 also complies with the rephrased REA axioms for supply chains. All resources flow from one organization to another and each exchange involves two organizations. The model can easily be extended applying the rephrased REA axioms while adding exchanges with additional organizations (e.g. suppliers for the factory).

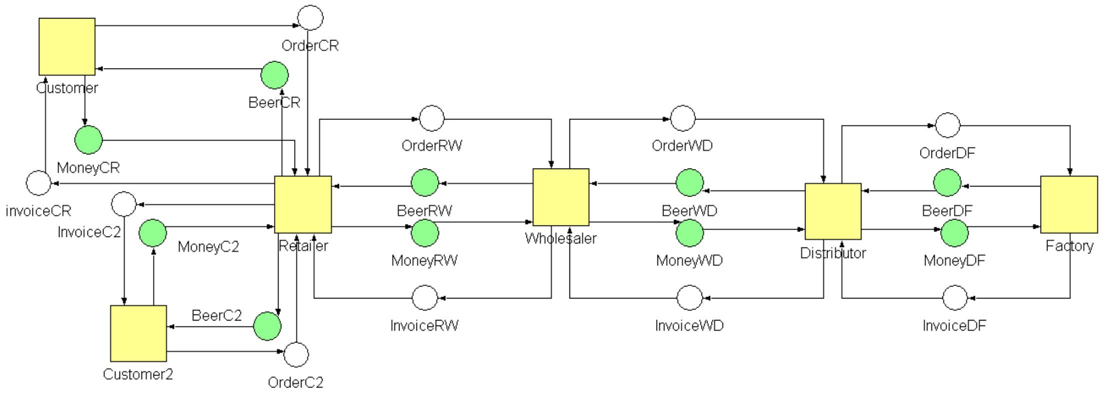

Figure 1. Supply chain model: the beer game

5.2. *Value Chain Model*

Using the ExSpecT modeling language, resource and information flow that originate in the supply chain model have been represented as ExSpecT input and output pins. Figure 2 shows the retailer's value chain (i.e. the subnet of the RETAILER ExSpecT system in figure 1). Incoming information flows (i.e. ORDERCR, ORDERC2 and INVOICERW) and resource flows (i.e. MONEYCR, MONEYC2 and BEERRW) have been modeled as input pins. Outgoing information flows (i.e. INVOICECR, INVOICEC2 and ORDERRW) and resource flows (i.e. BEERCR, BEERC2 and MONEYRW) are represented as output pins. Inside the value chain model, orders from both customers receive the same treatment although they have a different color. This color determines whether they result in a beer outflow via the BEERCR output pin (towards CUSTOMER) or the BEERC2 output pin (towards CUSTOMER2). At the four corners of the value chain model, information (i.e. BEERIN, BEEROUT, MONEYIN, MONEYOUT) and resource (i.e. BEERINFLOW, BEEROUTFLOW, MONEYINFLOW, MONEYOUTFLOW) flows intersect.

The model can be extended with additional customers by adding customers and exchanges with those customers at the supply chain level and connecting the resource and information flows to the value chain model as demonstrated with the second customer and accepting additional token colors in the value chain. A similar approach can be followed to add suppliers to the model. The same colored-token approach can also be followed to add customers and suppliers for the other organizations in the supply chain model.

In figure 2, the economic inflow and outflow events affect identifiable resources. The GiveBeer and TakeBeer events affect beer, the TakeMoney and GiveMoney events affect money. Consequently, figure 2 obeys the rephrased first REA axiom for value chains. The retailer is also involved in two kinds of exchanges. Exchanges with customers involve giving beer in return for money. Exchanges with suppliers involve giving money in return for beer. Consequently, the rephrased second REA axiom for value chains has been reflected in the model. The conversion and financing cycle ExSpect systems that connect beer and money inflows to beer and money outflows reflect the second REA axiom at business process level.

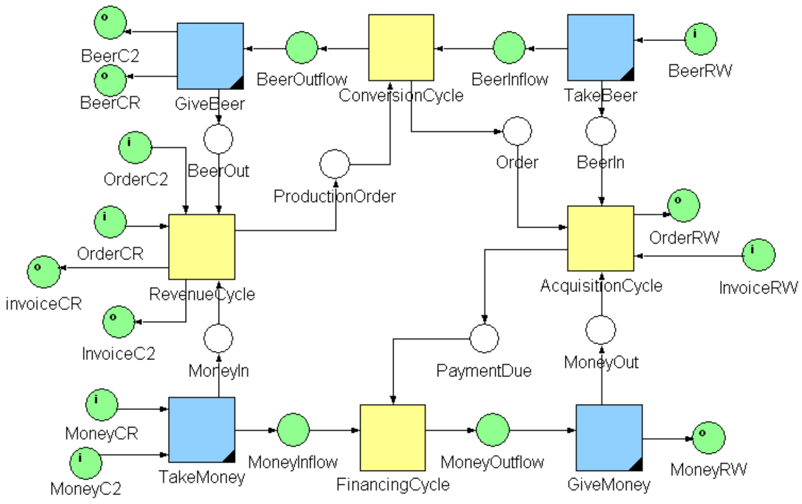

Figure 2. The retailer’s value chain model.

5.3. Business Process Models

At business process level we distinguish two types of business process models. The first type of business processes model involves economic events that affect resources and needs to comply with the REA axioms; the second type involves only information processing and does not need to comply with the REA axioms.

Figure 3 shows the retail process model, which is a subnet of the conversion cycle in figure 2. The model shows how incoming production orders lead to beer outflows when beer stocks are sufficient and lead to backlog when beer stocks are insufficient. The order picking activity, which ships beer stocks, is tagged with “give”, which is often used to describe a decrement event related to an exchange in the REA terminology. The backlog fulfilling activity is an alternative “give” process that fulfills outstanding orders as soon as stock levels are sufficient. Stocks are replenished with a “take” event, which is an increment event related to an exchange in the REA terminology. The stock management activity checks stock levels with a predetermined frequency (e.g. weekly) and sends out orders when stock levels are below the order point.

Since the activities in fig. 3 affect resources, the business process model has to comply with the rephrased REA axioms for business processes. The retail process involves a single resource stock (i.e. beer) that is represented by two ExSpecT stores. The STOCKRETAILER store represents the stock levels that are available to promise in a strict sense (i.e. not including outstanding orders). This figure will be shown in simulation runs as it allows us to represent quantities on hand and backlog in a single graph. The STOCKR store represents quantities on hand, which are either positive or zero. They are used to manage the backlog of orders. Both resource stores respect the rephrased first REA axiom, identifying an inflow (i.e. TAKER) and outflow (i.e. GIVER) event for the beer that is stocked. In figure 3 the stock manager is responsible for all parts of the business process, which is in line with the rephrased third REA axiom. The TAKER activity, which has been classified as an economic event, consumes a token from the BEERINFLOW channel in the retailer’s value chain model and produces a token in the STOCKRETAILER and STOCKR place. The GIVER activity consumes a token from the STOCKRETAILER and STOCKR place and produces a token in the BEEROUTFLOW channel in the retailer’s value chain model. Consequently, each economic event in fig. 3 complies with the rephrased second REA axiom for business processes. Combined with the rephrased first REA axiom for business processes, the second REA axiom for business processes ensures that the business process as a whole complies with the rephrased second REA axiom for business processes. As a result, the whole business process can be perceived as a single economic event and can be represented as a conversion cycle ExSpecT system in the retailer’s value chain model (fig. 2). This conversion cycle ExSpecT system also respects the rephrased second REA axioms for business processes. A similar model was built to model the behavior of the retailer’s financing cycle. This model deals with invoices instead of production orders, money inflow instead of beer inflow and money outflow instead of beer outflows.

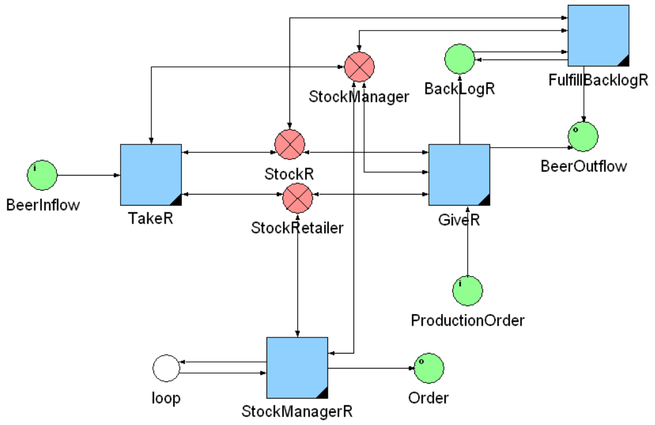

Figure 3 The retailer’s retail process

Figure 4 shows the factory’s production process, which is a subnet of the factory’s conversion cycle and a simplification of the real business process, in the sense that a number of production stages has been aggregated to reduce the size of the model. The process model contains a stock management activity that is almost identical to that of the retailer. However, the beer stock is replenished by an internal production process and not by supplier deliveries. A production order launched by the stock manager initiates the production process by consuming water and malt, which decreases WATER and MALT stocks. During the mashing process, work-in-process is represented by the MASHING channel. Once terminated, the mashing process produces WORT, which is a semi-manufacture. The wort is consumed by the cooking process that produces beer and waste. The model also shows that the brewer (i.e. an internal agent) is responsible for the whole production process. The model in figure 4 violates the rephrased first REA axioms for business processes at three different locations as no inflow has been modeled for the water and malt and no outflow has been modeled for waste. This axiom violation signals that we are at the border of model, and provides guidelines for extending the model if required. We also encounter this phenomenon at the other boundaries of the model (e.g. no inflow events were modeled for the customer’s money).

Figure 5 then shows the retailer’s acquisition cycle, while figure 6 represents the wholesaler’s revenue cycle, these cycles mirror each other since the retailer’s acquisition cycle communicates with the wholesaler’s revenue cycle, like the retailer’s revenue cycle exchanges information with the customer’s acquisition cycle. To stress this unity we tagged the business events in the models with concepts from the success layer of Dietz’ enterprise ontology [19]. This success layer contains the “happy path” through the DEMO transaction pattern [18], which contains the minimal coordination activities required to successfully complete a transaction. These activities are: (1) the initiator *requests* the executor to perform a transaction; (2) the executor promises to perform the transaction; (3) the executor performs the transaction and *states* that the transaction was executed; and (4) the initiator acknowledges the execution and *accepts* the results. The complete DEMO transaction pattern is more elaborate as it includes a discussion and a failure layer, but including those in our model would distract from this paper’s contribution.

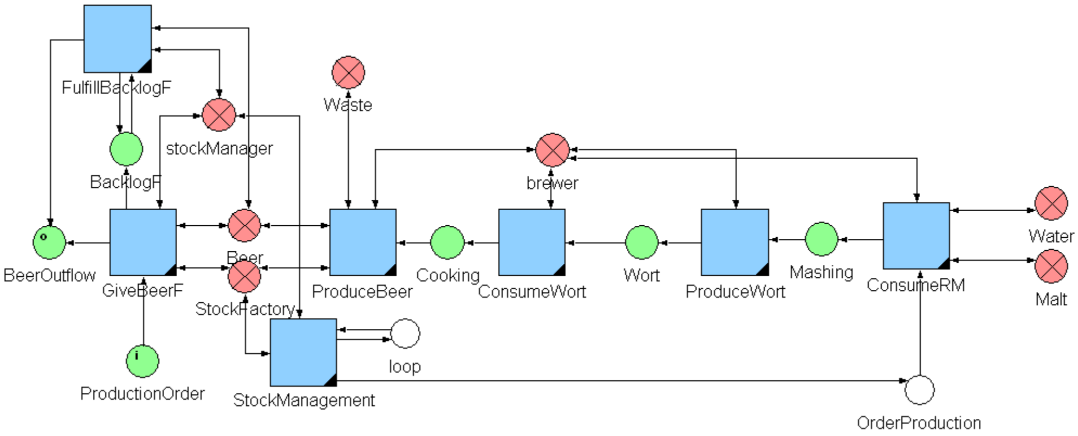

Fig. 4 The factory’s production process

We chose to model a demand-driven system. As a consequence, buyers play the initiator role in our models and sellers play the executor role. Supply-driven systems could be represented by switching the initiator and executor roles. The communication process between the trading partners is initiated by means of an order that is sent out by the retailer’s acquisition cycle. The wholesaler receives the order and promises to deliver. This promise creates an increment commitment (i.e. an expected beer stock increase) for the retailer and a decrement commitment for the wholesaler (i.e. a promised beer stock decrease). These commitments are respectively represented by the outstanding order (i.e. OUTORDERR) and backlog (i.e. BACKLOGW) stores, which are then fulfilled by a beer inflow (i.e. STATERW) and a beer outflow (i.e. STATEW). The commitment fulfilling beer inflow and outflow then need to be paired in duality with a balancing money outflow and inflow. Consequently, an invoice is sent out to the retailer, which creates an increment commitment for the wholesaler (i.e. accounts receivable) and a decrement commitment for the retailer (i.e. accounts payable). These commitments are fulfilled by a money inflow and outflow. Together, these two models show the information exchanges that are required to enforce the rephrased second REA axiom at value chain level.

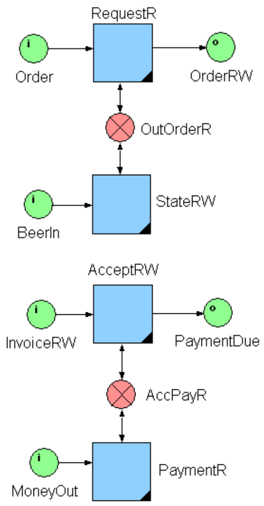

Fig. 5 The retailer’s acquisition cycle

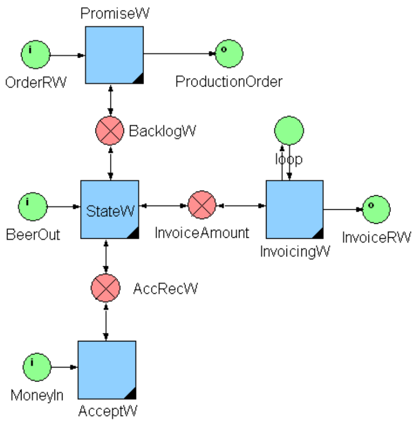

Fig. 6 The wholesaler’s revenue cycle

5.4. A value system simulation

In this subsection, we simulate the behavior of two alternative beer game scenarios, using two alternative configurations of the beer game value system simulation model built above. The first scenario simulates the behavior of the value system with weekly orders by the retailer. The second scenario simulates the behavior of the same value system with daily orders by the retailer.

In both scenarios, the Customer orders five beers a day, while Customer2 orders one beer a day. The Retailer charges $1.25 per beer to his customers, the Wholesaler charges $1 per beer to the Retailer, the Distributor charges $0.70 per beer to the Wholesaler and the Factory charges $0.50 per beer to the Distributor. When their stock levels are sufficient all suppliers in the supply chain deliver to their customers in the supply chain the day after the order, except for the Retailer who delivers immediately to his customers. When their stock levels are insufficient, orders are added to the backlog and delivered as soon as stock levels are adequate. Beer outflows lead to an increment of accounts receivable, and the Retailer sends out invoices to his customers on a daily basis, the Wholesaler, Distributor and Factory invoice once a week (5 days). Customers pay their invoices immediately to the RETAILER; all other supply chain partners pay with a one day delay. At the FACTORY, the beer production process takes a single day. Customers of the RETAILER are able to order several times a day and their economic order quantity (EOQ) is 1, which means they can order a single beer at a time. Initially, stock levels are 0 for all supply chain partners.

Scenario 1 and 2 differ in their stock management policy. In scenario 1, the RETAILER orders beer from the WHOLESALER once a week (5 days), while the other supply chain partners are able to order once a day. For all supply chain partners (except customers of the RETAILER) the EOQ is 35 and the order point is also 35, which means they order 35 additional beers as soon as stock levels drop below 35. In scenario 2, all supply chain partners (i.e. the retailer included) are able to order on a daily basis, while the customers of the Retailer are still able to order more frequently. For all supply chain partners (except customers of the RETAILER) the EOQ is 10 and the order point is also 10, which means they order 10 additional beers as soon as stock levels drop below 10.

Figure 7 and 8 show the simulation results for scenario 1 and 2. Both value system scenarios were simulated for 35 days. The figures contain graphs for the value system. We observe graphs for all supply chain partners in fig. 1, and measures for each part of the value chain. Stocks represent the conversion cycle, accounts current (AC) represent the financing cycle, accounts payable (and backlog) represent the acquisition cycle, and accounts receivable represent the revenue cycle.

Fig 7 and 8 reveal the effect of stock management policies on the entire value system. In fig. 7 elevated stock levels can be observed for the wholesaler and the distributor, which provides evidence of a bullwhip effect cause by their backlog. These increased stock levels also lead to an increase in capital that is immobilized in stocks. The result of this capital immobilization can be observed in fig. 7 as the balances of the wholesaler's and distributor's account current decrease when stock levels increase. Negative accounts currents indicate a need to access the capital markets. However, making profit allows organizations to gradually build up their own financial means. Increasing accounts current can be observed in all supply chain partners, but is especially evident with the retailer.

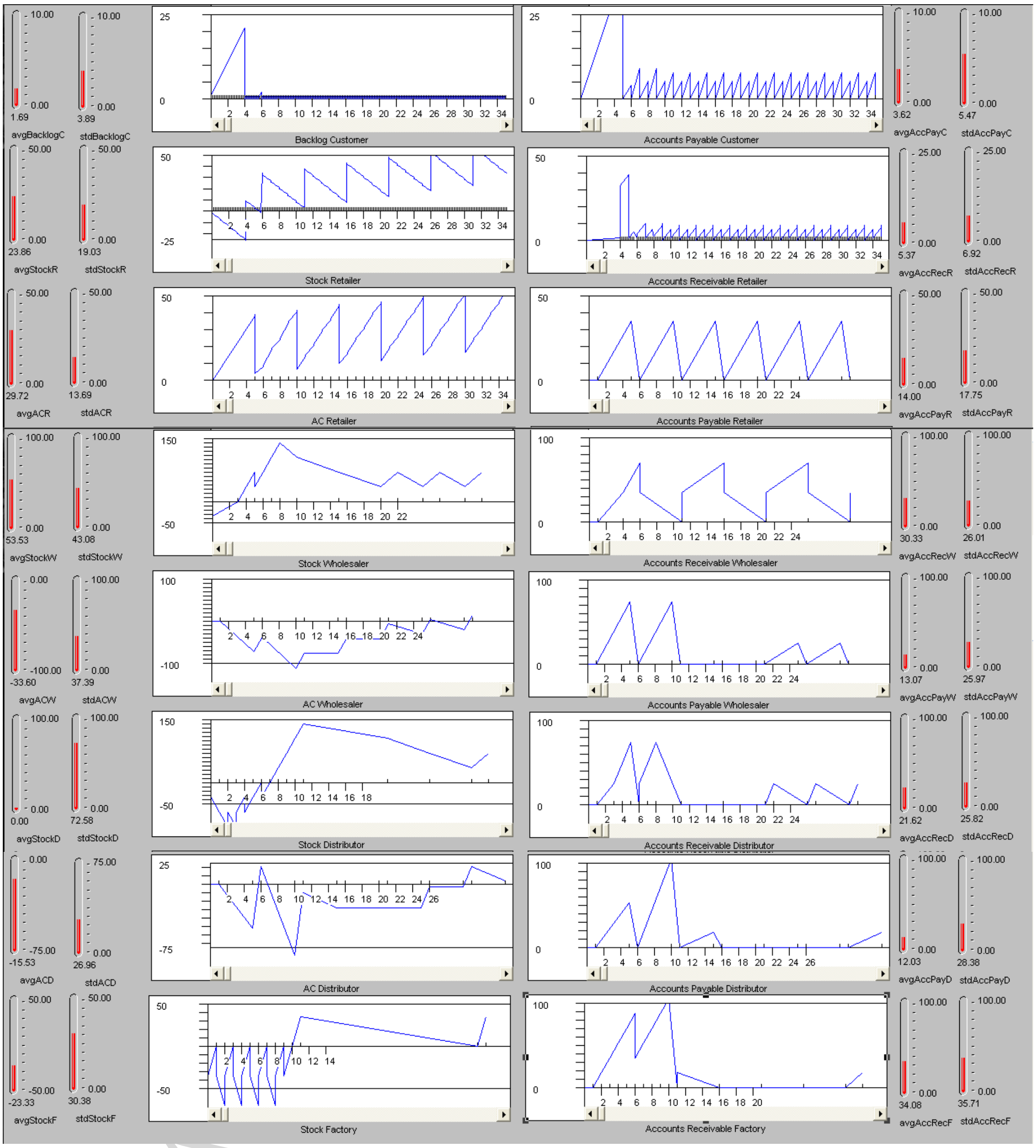

Fig. 7 Scenario 1:Beer Game simulation with weekly orders by the retailer

When we compare both scenarios we see that it takes longer to eliminate the backlog, up to 20 days for the factory. On the other hand, this gradual elimination of the backlog in scenario 2 has the advantage that peeks in the customer's accounts payable and the retailer's accounts receivable can be avoided. Furthermore, the customer receives deliveries from day 5 on, in both scenarios. In scenario 2 we also observe the disappearance of the bullwhip effect that was observed in scenario 1. The disappearance results in reduced stock levels and less negative account current balances, which indicate a reduced need to access the capital markets and is likely to reduce financing costs.

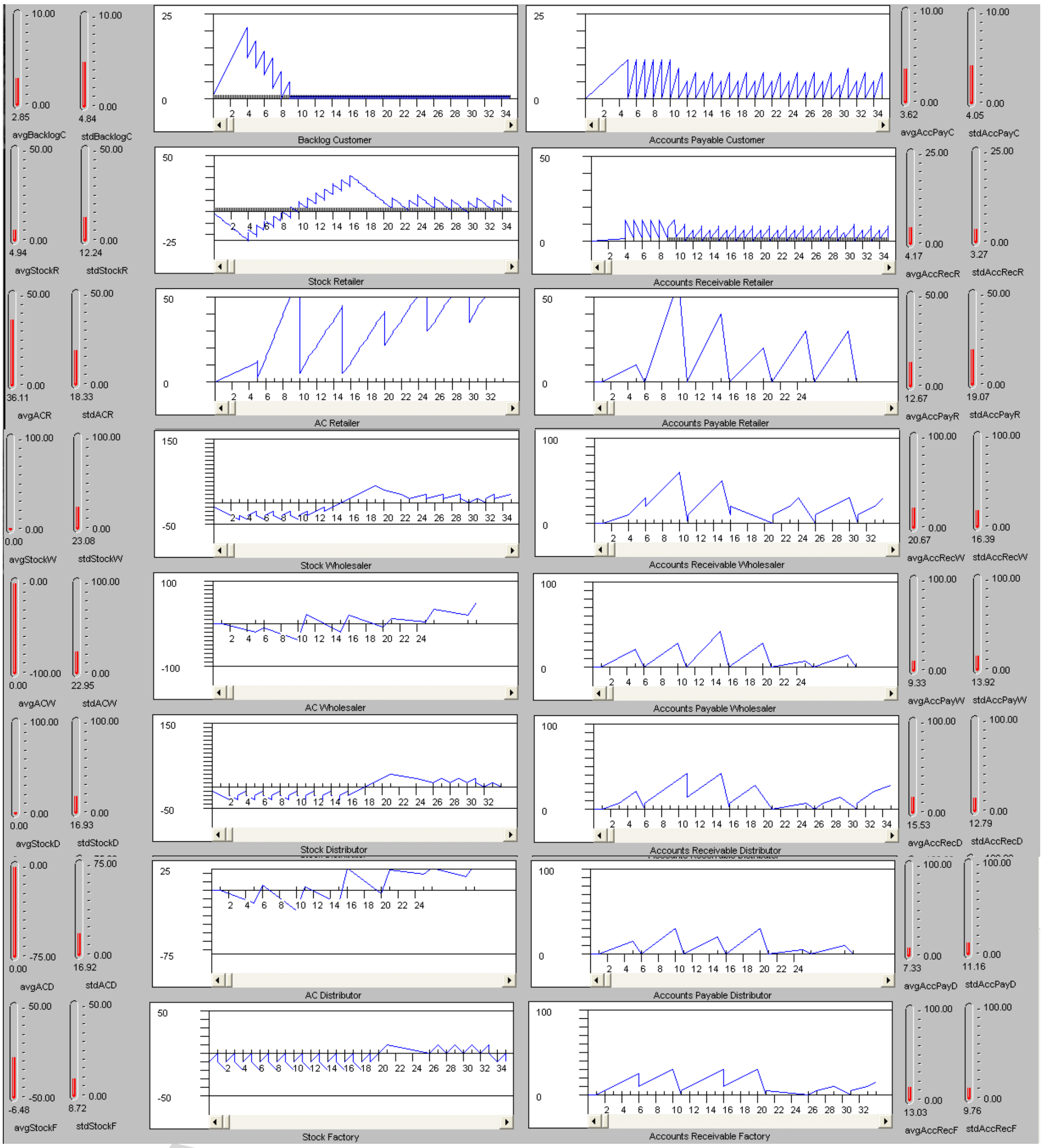

Fig. 8 Scenario 2: Beer Game simulation with daily orders by the retailer

5.5. *Discussion & Future Research*

During the modeling process of the beer game, we used the REA axioms as a framework for scoping and developing our model federates. As the REA ontology prescribes, the simulation models were structured as a hierarchy of three model types [21]. Within each modeling layer, the REA axioms were applied to assure that each net or subnet was a true and fair representation of the economic reality captured by the REA ontology. As several trading partners in the beer game scenario have similar activities, we were able to reuse many federates as a template for other federates in the federation. Additionally, federates were designed in such a way that they could be used as a standalone artifact with only minimal adjustments. For example, the factory's conversion cycle model could be reused to analyze the properties of production process on its own. Similarly, the communication models contained in the acquisition and revenue cycle could easily[5] be merged into a single communication model that could be used to analyze the properties of the communication process.

To the best of our knowledge, this section presents the first application of an ontology-based modeling framework to build a value system simulation model published to date. Church and Smith [53] present an REA-based modeling framework that is limited to the acquisition and revenue cycle of a single enterprise, covering only part of the value chain level presented here. Additionally, they use system dynamics to build their simulation model. Although system dynamics is used for analyzing the behavior of complex systems over time, it uses mathematical equations to describe the systems behavior, which means that it is impossible to evaluate the effect of discrete events in the system. Bassett and Gardner [7] build a mixed integer linear programming (MILP) model for a value system, which supports supply chain optimization but not simulation. They founded their model on domain knowledge captured in existing MILP models instead of a domain ontology, and case information from Dow AgroScience. Similar to the benefits of the framework presented here, Bassett and Gardner managed to reuse simulation model federates by identifying similar behavior for similar product families and to create a model in which financial, operational and logistical parameters and variables are joined. At the lowest and most detailed level of our framework we find business process models. Other and more elaborate approaches have been presented for constructing business process and workflow models [14, 54, 55]. Workflow models, which are a subclass of business process models, focus on information processing; therefore they can be integrated as such since they do not need to comply with the axioms of the REA ontology. In the value chain model, the acquisition and revenue cycle were reserved for information flows. Therefore it would be desirable to model workflow processes as subnets of the acquisition or revenue cycle unless the organization's core

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[5] Because the integration points have already been identified.

business is information processing, which would demand them to be modeled as subnets of the conversion cycle, or unless they deal with budgeting and financing, which would require them to be modeled as subnets of the financing cycle.

In the future, we would like to investigate the integration of the framework presented here with existing business process modeling approaches to further elaborate the business process level. For example, an integration with SCOR [14] should introduce additional guidelines for modeling the business processes of the conversion cycle. An integration with DEMO [18], should provide additional guidelines for modeling the acquisition and revenue cycle and potentially communication within and between all processes of the value chain. On the other hand, integration with the REA framework presented here would allow users of those frameworks to assess the financial impact of business process changes in advance, as has been demonstrated for a change in stock management policies above.

In the future, we would also like to add a library to the ExSpect tool that uses ExSpecT's full analytical power, adding REA's modeling power as an REA-based domain-specific modeling language that can then be used instead of the more generic Petri-net based modeling language accompanied by REA-based modeling guidelines. This domain-specific language should then be able to guide REA-unaware simulation model builders to scope their supply chain, value chain and business process models such that they can easily be integrated with each other to construct multi-author value system simulation models that can be constructed by (re)using and integrating simulation models that were designed for purely logistical or operational simulations. At a later stage we would also like to add other (mainly business process) modeling approaches to this library.

6. Conclusions

In this paper we argued that supply chain, value chain and business process models are not standalone artifacts. Instead they are part of an integrated reality that is more complex than each type of standalone simulation model can represent. We demonstrated that the REA ontology can be used as an ontology-based modeling framework that supports the integration of these three kinds of simulation models. Where conventional business process, workflow and supply chain simulations limit their scope to operational parameters (e.g., service time, production cost), the REA ontology's accounting basis allows for the incorporation of a whole range of financial parameters (e.g., added value, total profit, debt).

By means of example models, the paper shows that the conceptual modeling rules incorporated in the REA ontology allow for the creation and integration of distinct and clearly scoped models into a complete value system model. These modeling guidelines, which address the invariant conditions in value system models as described by the REA axioms, are summarized in table 1. Decomposing, rephrasing and assigning these (partial) axioms to specific simulation model types (i.e., supply chain, value chain or business process), as demonstrated in the text, should help non-REA savvy modelers to benefit from the REA ontology.

As the standard ExSpecT libraries contain powerful process analysis tools for simulating operational and logistic process properties and the REA axioms do not interfere with the rules of operational and logistical processes, the tools can still be used to assess operational and logistical process properties of REA models. The REA axioms also allow for the inclusion of a second dimension (i.e. the financial perspective) in those models. This second dimension allows us to assess the effect operational and logistic changes have on an organization's financial performance, and vice versa. The incorporation of information flows as resource flow coordinators even enables the assessment of (delays in) information flows on an organization's operational, logistic and financial performance. Since the ExSpecT tool provides exquisite visualization help and powerful statistical simulation and analysis support (e.g., token generators that can generate numbers from a wide variety of statistical distributions, instruments that can measure and visualize a wide variety of statistical parameters and variables), the supply and value chain and business process simulation models presented in this paper can be integrated into complete value system models that are expected to allow organizations to simulate and evaluate the effect of business process and supply chain modifications on their financial performance, as demonstrated in [56]. By using the Petri-net based ExSpecT language, we also showed that the REA ontology can be used for building discrete-event simulation models, which was – to the best of our knowledge – not demonstrated yet.

References

1. Porter, M.E. and V.E. Millar, *How information gives you competitive advantage.* Harvard Business Review, 1985. **63**(4): p. 149-160.
2. Church, K. and R. Smith, *REA Ontology-Based Simulation Models for Enterprise Strategic Planning.* Journal of Information Systems, 2008. **22**(2): p. 301-329.
3. Reijers, H.A. and S. Liman Mansar, *Best practices in business process redesign: an overview and qualitative evaluation of successful redesign heuristics.* Omega, 2005. **33**(4): p. 283-306.
4. Chatfield, D.C., T.P. Harrison, and J.C. Hayya, *SISCO: An object-oriented supply chain simulation system.* Decision Support Systems, 2006. **42**(1): p. 422-434.
5. Liu, R., A. Kumar, and W. van der Aalst, *A formal modeling approach for supply chain event management.* Decision Support Systems, 2007. **43**(3): p. 761-778.
6. Machol, R.E., W.P. Tanner, and S.N. Alexander, *System engineering handbook*. 1965, New York,: McGraw-Hill.
7. Bassett, M. and L. Gardner, *Optimizing the design of global supply chains at Dow AgroSciences.* Computers & Chemical Engineering, 2010. **34**(2): p. 254-265.
8. Benjamin, P., M. Patki, and R. Mayer, *Using ontologies for simulation modeling*, in *Proceedings of the 38th conference on Winter simulation*. 2006, Winter Simulation Conference: Monterey, California.
9. Strader, T.J., F.-R. Lin, and M.J. Shaw, *Information infrastructure for electronic virtual organization management.* Decision Support Systems, 1998. **23**(1): p. 75-94.
10. Hua, Z., Y. Sun, and X. Xu, *Operational causes of bankruptcy propagation in supply chain.* Decision Support Systems, 2011. **51**(3): p. 671-681.
11. Chih-Yang, T., *On supply chain cash flow risks.* Decision Support Systems, 2008. **44**(4): p. 1031-1042.
12. Dong, J., et al., *IBM SmartSCOR - a SCOR based supply chain transformation platform through simulation and optimization techniques*, in *Proceedings of the 38th conference on Winter simulation*. 2006, Winter Simulation Conference: Monterey, California.
13. Kaplan, R.S. and D.P. Norton, *The Balanced Scorecard--Measures That Drive Performance.* Harvard Business Review, 1992. **70**(1): p. 71-79.
14. Council, S.-C., *Supply-Chain Operations Reference-model*. 2006.
15. Gailly, F., W. Laurier, and G. Poels, *Positioning and Formalizing the REA enterprise ontology.* Journal of Information Systems, 2008. **22**(2): p. 219-248.
16. Bahrami, A., *Object oriented systems development*. 1999, Boston, Mass. ; London: Irwin/McGraw-Hill. 411 p.
17. Gordijn, J., *Value-based requirements Engineering: Exploring innovative e-commerce ideas*, in *Exact Sciences*. 2002, Free University of Amsterdam: Amsterdam. p. 292.
18. Dietz, J.L.G., *Enterprise ontology : theory and methodology*. 2006, Berlin ; New York: Springer. xiii, 243 p.
19. Dietz, J.L.G., *The atoms, molecules and fibers of organizations.* Data & Knowledge Engineering, 2003. **47**(3): p. 301-325.
20. Brandenburger, A. and B. Nalebuff, *Co-opetition*. 1st ed. 1996, New York: Doubleday. xiv, 290 p.
21. Geerts, G.L. and W.E. McCarthy, *An ontological analysis of the economic primitives of the extended-REA enterprise information architecture.* International Journal of Accounting Information Systems, 2002. **3**(1): p. 1-16.
22. Geerts, G.L. and W.E. McCarthy, *The Ontological Foundation of REA Enterprise Information Systems*. 2005, University of Delaware, Newark; Michigan State University, East Lansing.
23. Sterman, J., *The Beer Game*, in *The Fifth Discipline*. 1984, MIT. p. 27-54.
24. Hevner, A.R., et al., *DESIGN SCIENCE IN INFORMATION SYSTEMS RESEARCH.* MIS Quarterly, 2004. **28**(1): p. 75-105.
25. March, S.T. and G.F. Smith, *Design and natural science research on information technology.* Decision Support Systems, 1995. **15**(4): p. 251-266.

26. Fayez, M., L. Rabelo, and M. Mollaghasemi, *Ontologies for supply chain simulation modeling*, in *Proceedings of the 37th conference on Winter simulation*. 2005, Winter Simulation Conference: Orlando, Florida.
27. Fishman, G.S., *Principles of discrete event simulation*. Wiley series on systems engineering and analysis. 1978, New York: Wiley. xviii, 514 p.
28. Bakkenist, D.T., *ExSpecT User Manual*, M.I. Consultants, Editor. 1999, http://www.exspect.com/ex641usermanual.pdf.
29. Beulens, A., et al., *Modelling systems with exspect*, in *Optimization-Based Computer-Aided Modelling and Design*. 1992, Springer Berlin / Heidelberg. p. 211-222.
30. Borst, W.N., *Construction of engineering ontologies for knowledge sharing an reuse*, in *Centre for Telematics and Information Technology*. 1997, Universiteit Twente: Enschede. p. 227.
31. Gruber, T.R., *A translation approach to portable ontology specifications.* Knowledge Acquisition, 1993. **5**(2): p. 199-220.
32. Fonseca, F. and J. Martin, *Learning The Differences Between Ontologies and Conceptual Schemas Through Ontology-Driven Information Systems.* Journal of the Association for Information Systems, 2007. **8**: p. 129-142.
33. Kartseva, V., et al. *Control Patterns in a Healthcare Network*. in *8th Annual International Conference on Digital Government Research*. 2007.
34. Lyytinen, K., et al., *Designing Value-Based Inter-organizational Controls Using Patterns*, in *Design Requirements Engineering: A Ten-Year Perspective*, W. Aalst, et al., Editors. 2009, Springer Berlin Heidelberg. p. 276-301.
35. Hulstijn, J. and J. Gordijn. *Risk analysis for inter-organizational controls*. in *12th International Conference on Enterprise Information Systems (ICEIS 2010)*. 2010. Funchal, Madeira, Portugal.
36. Osterwalder, A., *The Business Model Ontology - a proposition in a design science approach*, in *Ecole des Hautes Etudes Commerciales*. 2004, University of Lausanne: Lausanne.
37. OMG, *Business Motivation Model*. 2008, Object Management Group.
38. Ushold, M., et al., *The Enterprise Ontology.* The Knowledge Engineering Review: Special Issue on Putting Ontologies to Use, 1998. **13**(1): p. 31-89.
39. Silver, G.A., L.W. Lacy, and J.A. Miller, *Ontology based representations of simulation models following the process interaction world view*, in *Proceedings of the 38th conference on Winter simulation*. 2006, Winter Simulation Conference: Monterey, California.
40. Cope, D., et al., *Supply chain simulation modeling made easy: an innovative approach*, in *Proceedings of the 39th conference on Winter simulation: 40 years! The best is yet to come*. 2007, IEEE Press: Washington D.C.
41. McCarthy, W.E., *The REA Accounting Model: A Generalized Framework for Accounting Systems in a Shared Data Environment.* Accounting Review, 1982. **57**(3): p. 554-578.
42. ISO/IEC, *Information technology - Business Operational View Part 4: Business transaction scenario - Accounting and economic ontology*, in *ISO/IEC FDIS 15944-4: 2007(E)*. 2007.
43. Geerts, G.L. and W.E. McCarthy, *An accounting object infrastructure for knowledge-based enterprise models.* Ieee Intelligent Systems & Their Applications, 1999. **14**(4): p. 89-94.
44. McCarthy, W.E., *The REA Modeling Approach to Teaching Accounting Information Systems.* Issues in Accounting Education, 2003. **18**(4): p. 427-441.
45. Dunn, C.L., J.O. Cherrington, and A.S. Hollander, *Enterprise information systems : a pattern-based approach*. 3rd ed. 2005, Boston: McGraw-Hill/Irwin. xxi, 522 p.
46. Hruby, P., *Model-driven design using business patterns*. 2006, Berlin: Springer. xvi, 368 p.
47. McCarthy, W.E., *An Entity-Relationship View of Accounting Models.* Accounting Review, 1979. **54**(4): p. 667.
48. Geerts, G.L. and W.E. McCarthy, *The Ontological Foundation of REA Enterprise Information Systems*. 2004, Michigan State University.
49. Geerts, G.L. and W.E. McCarthy, *Augmented Intensional Reasoning in Knowledge-Based Accounting Systems.* Journal of Information Systems, 2000. **14**(2): p. 127.

50. Aalst, W.M.P.v.d., et al., *ExSpect 6.4: an executable specification tool for hierarchical colored Petri nets*, in *Proceedings of the 21st international conference on Application and theory of petri nets*. 2000, Springer-Verlag: Aarhus, Denmark.
51. Murata, T., *PETRI NETS - PROPERTIES, ANALYSIS AND APPLICATIONS.* Proceedings of the Ieee, 1989. **77**(4): p. 541-580.
52. Jensen, K., *Coloured Petri nets : basic concepts,analysis methods and practical use*. 1995, Berlin ; London: Springer-Verlag. viii,174p.
53. Church, K. and R. Smith, *An Ontology-Based Dynamic Enterprise Model for Managerial Planning and Control*, in *REA-25, A Celebration of the REA Enterprise Model*. 2007: Newark, Delaware (USA).
54. van der Aalst, W.M.P. and K.M. van Hee, *Workflow management : models, methods and systems*. Cooperative information systems. 2002, Cambridge, Mass.: MIT Press.
55. Reijers, H.A., S. Limam, and W.M.P. van der Aalst, *Product-Based Workflow Design.* J. Manage. Inf. Syst., 2003. **20**(1): p. 229-262.
56. Laurier, W. and G. Poels, *A Simulation Model Articulation of the REA Ontology.* Lecture Notes in Computer Science, 2009. **5872**(On the Move to Meaningful Internet Systems: OTM 2009 Workshops): p. 554-563.

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Highlights

- Defining the scope of business process, supply and value chain simulation models
- Rephrasing the REA modeling axioms for each of these types of simulation models
- Identifying integration points between these models through the REA ontology
- Integrating these three types of models into a hierarchic value system model
- First application of the REA ontology for building discrete-event simulation models