A three-phase framework for elicitation of infrastructure requirements

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Abstract: Many of the current traditional system engineering (TSE) approaches for elicitation of requirements are insufficient when deployed in complex situations. TSE approach to requirement elicitation is based on assumption of stable environmental conditions. However, the elicitation of requirements for complex systems (i.e., interdependent critical infrastructures) requires innovative approaches that should go beyond technical aspects of a situation. Complex situations arise when multiple complex infrastructures interdependently interact to provide goods and services for public health and safety. The elicitation of requirements for such a system must consider the nature of system of interest, its environment and system observer. On this backdrop, this paper reviews complexity associated with attained requirements for complex infrastructures, failures and provides an overview of a proposed high-level framework for infrastructure requirement elicitation.

Keywords: complex systems; critical infrastructures; environment nature; framework; requirements elicitation; requirement observer; requirement nature; traditional system engineering; TSE; understanding.

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1   Introduction

The traditional way of dealing with systems requirements needs to take into account the increasing environmental and phenomenological complexities along with the nature of the observer. Current methods do not cope well with complex systems where neither system owners nor system engineers are able to elicit true systems requirements. In fact, traditional system engineering (TSE) approaches are slow in responding to rapid changes in technological innovations as well; this is something that must be addressed given that technological advancements are one of the driving forces in the 21st century (Azani and Khorramshahgol, 2005).

TSE approaches that deal with systems requirements (such as the 'V' model) are sufficient when applied to elicitation of requirements in simple and technical systems where requirements are stable and unambiguous. Keating et al. (2008) note that TSE has been successful in developing technical requirements that are objective, verifiable, and definitive. In the 21st century, there is growing interest in critical infrastructure protection whose requirements are subjective, unverifiable, and indecisive. These emerging complex systems (e.g., water, healthcare, transportation, etc.) (Gheorghe, 2006) require approaches that can address ambiguity, instability, ill-defined conditions, unclear requirements, excessive complexity, and dynamic changes in the environment. The move from system-as-is to system-to-be is made harder when one considers the nature of complex systems boundaries and the nature of people who deal with such systems.

TSE methods have proven to be successful in design, development, production, and construction of different systems (Blanchard and Fabrycky, 2006; Forsberg and Mooz, 1991, 1999) and they will remain viable when implemented in technical situations where requirements are traceable, understandable, easily modified, and can be elicited, verified, and validated. However, assuming that TSE strategies are capable of dealing with elicitation of requirements for interdependent critical infrastructure can bring harm and disaster to the public (i.e., stakeholders and the general population). This paper supports the idea that dealing with complex systems requires careful examination of:

1   the nature of the problematic system

2   the nature of the system observer (i.e., owner, designer, user)

3   taking into consideration the dynamic operational environment.

Hence, the main purpose of this paper is to develop a framework that incorporates the above mentioned perspectives in order to elicit complex system requirements in a turbulent environment. The authors stipulate that infrastructure system properties could be used as a guide in selection of proper methods for elicitation of requirements prior to design.

To support this purpose, the authors have structured this paper into five sections. First, a quick overview of terminology that drives the thinking for this paper is provided. Misunderstanding of these terms can lead to misapplications in the current dialogue. Second, the nature of phenomenological problematic infrastructure systems is addressed using a set of infrastructure properties and attributes. This is to show the relationship that

exists between infrastructure system requirements and infrastructure properties and attributes. Third, the nature of the infrastructure system observer is addressed. The intent is to show that the nature of the observer has implications on final system requirements. Fourth, authors examine the 'V' model applicability in elicitation of requirements for infrastructures. The purpose is to explain implications and ramifications of using this approach. Fifth, a three-phase framework that can aid in elicitation of infrastructure requirements is proposed. This framework is a continuum process based on systems thinking aimed at reducing the gap between the infrastructure requirements, the observer's view of the infrastructure, and the infrastructure's environment.

2 Associated terminology

Prior to proceeding into developing the proposed framework, the authors have identified some representative terms that bring consistency and serve as a guide throughout this paper.

- *System as infrastructure:* The term system, as applied in this paper, follows von Bertalanffy's1968 seminal book on General System Theory where the examination is not only on 'a steam engine' (von Bertalanffy, 1968) but also on the one that seeks to guide and take control of a ship. Blanchard and Fabrycky (2006) note that a system could also be a complex unitary whole or a set of correlated members (i.e., system of currency). A system also includes ordered and comprehensive assemblage of facts, principles, and doctrines in a particular field of knowledge and thought (i.e., system of philosophy) (Blanchard and Fabrycky, 2006). Therefore, infrastructure is a system if it has well-interconnected parts (subsystem) that have an aim if fulfilling a goal (Gibson et al., 2007).

- *Nature of requirements:* This paper treats requirements as a dynamic entity. Being treated as such, requirements can change over time especially in complex situation and/or SoS constructs. The requirements for infrastructures are dynamic. Therefore, their elicitation requires that the observer be cognizant of the changing and evolving requirements.

- *Requirements engineering:* Literature on requirement engineering is vast (Keating et al., 2008; Hull et al., 2011; van Lamsweerde, 2009). This paper adopts a definition from the software development arena by van Lamsweerde. In van Lamsweerde (2009), van Lamsweerde notes that the process in requirements engineering involves correctly understanding and defining a problematic situation in order to accurately provide a solution. The projected system is what van Lamsweerde calls system-to-be as opposed to system-as-is. Under this construct, it is assumable that the system observer has the ability to distinguish between these system states using exploration, evaluation, and documenting approaches (van Lamsweerde, 2009). Engineering models such as spirals, waterfalls, and the 'V' model use these pragmatics and depend heavily on defining and refining of original requirement. An informative list of various definitions for system requirements is provided in Keating et al. (2008) and advances the current dialogue.

- *Complex systems:* Since a vast portion of this paper deals with understanding complex infrastructure systems, it is necessary to define what complex systems are. Bar-Yam (1997) uses principles related to thermodynamics, entropy, and equilibrium to describe the meaning of complexity. By referring to systems attributes (properties such as emergence) to explain complex systems, Bar-Yam (1997) notes that complex systems are hard to manage. This is largely due to emergent behaviours that cannot be readily understood from the behaviour of the parts. Emergent behaviours have been extended to complexity in ideas, artifacts, social, political, economic, governance, structure, philosophy, system operations, and control (Zundong et al., 2008). However, this paper extends emergent behaviour to interdependent infrastructure.

- *System-of-systems:* System-of-systems (SoS) is another area of concern in this paper. There are numerous perspectives of SoS (DeLaurentis et al., 2006; DoD, 2006; Fritz et al., 2008; Gorod et al., 2008; Kotov, 1997) for which detailed discussion is beyond the space allocated for this section. Therefore, this paper adopts one perspective, which is consistent with the current dialog. SoS has been described as a "design, deployment, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results…diverse in technology, context, operation, geography, and conceptual frame" [Keating et al., (2003), p.40]. Desirable results in the context of requirements stipulate capturing the infrastructure system requirements beyond technical aspects. Complexity in relationships, interconnections, and interdependencies among constituent subsystems, boundaries, products, and change in environment guarantee emergent behaviour that cannot be anticipated and captured via TSE approaches (Keating, 2009).

- *System environment:* This paper uses the term environment to describe 'space' in which all infrastructure systems and activities reside. The space houses system activities related to positions, missions, objectives, goals, and functions of infrastructure system whether they are known or unknown. Infrastructure systems manifest their attributes in the environment to the observer. The environment plays a vital role in infrastructure system behaviour and affects the existence and the development of other systems in the environment (Krippendorff, 1986). For example, self-organising complex systems communicate via the environment. The environment provides resources, regulations and the medium for communication and interconnectivity.

This terminology overview provides two important points. First, obtaining true infrastructure system requirements is a challenge for TSE strategies. Moreover, obtaining true system requirements is a necessary activity that leads to successful design of dependable infrastructure. Second, these terms provide a guide for the underlying message of this paper. In the following section, the nature of complex systems is examined by focusing on infrastructure (system) types and their attributes.

3 Complex system attributes

The purpose of this section is to provide a unifying notion of the nature of complex infrastructure systems and their attributes. Prior to addressing the attributes of complex systems, the authors define the main types of complex systems as addressed in literature (Bar-Yam, 1997; Ashby, 1962; Bane, 2008; Biggiero, 2001; Bohr, 1949; Kovacic et al., 2008; Lucas, 1999; Norman and Luras, 2006; Sousa-Poza and Correa-Martinez, 2005; Taleb, 2010). To give a more complete picture of complex systems, this paper uses unifying themes across various works rather than focusing on individual definitions. Themes commonly associated with complex systems include:

- *Dynamic complex systems:* In Lucas (1999), Lucas stipulates that dynamic systems have four dimensions that need consideration during computations; size, density (weight), shape, and time. Entities in dynamic systems change over time. Therefore, requirements elicitation approaches must consider system states. In many TSE approaches, the assumption is that infrastructure requirements do not change and if they change, they must be made stable, verifiable, and objective. This enables TSE requirements' elicitation process to be easy and repeatable. Designing infrastructure requires approaches that are dynamic.

- *Evolving complex systems:* A good example of an evolving system is the human immune systems and the internet. Such types of systems have the ability to evolve over time and their path cannot be predicted by studying past system paths and/or states. Using evolutionary theory von Bertalanffy (1968) notes that:

  > "Chaos was the oft-quoted blind play of atoms … life as an accidental product of physical processes…In the same sense, human personality, was considered a chance of nature and nurture, of a mixture of genes and accidental sequence of events from childhood to maturity"

  Interdependencies in infrastructures underline the complexity in understanding evolving systems (Santella et al., 2009). The elicitation of infrastructure requirements for evolving systems can be a source of problems and therefore caution is needed when dealing with evolving infrastructures.

- *Self-organising complex systems:* In biological organisms, self-organisation is associated with duplication and reproduction where a global emergence can occur based on local information. Unlike simple technical systems, Azani (2009) stipulates that predetermination of the path of a complex system and freedom of response cannot be known from one system. The identity and control has to be identified at the metasystem level. Individual infrastructures, which are themselves complex, interact to provide a capability (behaviour) that can only be provided at the SoS construct. Constant change in such systems ensures that elicitation of requirement is a difficult task.

Having described types of complex infrastructure systems, the focus is now shifted to complex system attributes. Referring to these attributes as properties of infrastructure systems is appropriate since they can be found in physical and cyber systems. The authors assert that understanding these attributes is of the utmost importance since they describe nature of infrastructure systems:

- *Algedonic attribute:* According to Krippendorff (1986), this is a systems attribute where regulation and correction is done after pain and/or pleasure. Under this attribute, system observers will generally learn the true system requirements after a reward in the form of pain or pleasure (i.e., the pain or pleasure becomes the learning experience for the system observer; reward or a punishment comes first before the true system behaviour). In essence, true system requirements can only be obtained after the learning experience. While elicitation of requirements for simple systems can take place anytime, the elicitation of requirements for complex systems takes place after a reward (pain or pleasure). For example, the events of 9/11 have taught the public a lot regarding protection of infrastructure.

- *Boundary liquidity attribute:* In Keating et al. (2004, p.19), it is noted that boundaries for SoS change overtime and that "understanding that they will change throughout the analysis, design, and transformation…" enables better preparation. Hence, there is a need to understand that complex infrastructure system requirements are negotiable as opposed to clear, concrete and objective (Keating et al., 2008). This affects people, information and technology, space, throughput, and time.

- *Complementarity:* Complementarity provides multiple perspectives of any given system (Keating et al., 2004). Each perspective is neither correct nor incorrect but it is necessary to ensure robust design and a dependable infrastructure. The failure to include multiple views is limiting and can cause a type III error of solving the wrong problem (Mitroff, 1998).

- *Emergent behaviour:* Keating (2009) suggests that the properties (patterns, capabilities, structure, behaviours, performance) of systems can develop from the interaction of system elements over time. These properties and events cannot be predicted or understood from the properties of single infrastructure elements in the SoS setting.

- *Interdependence systems attribute:* One poorly designed system affects the performance of coupled and interconnected infrastructure. Interdependence in systems can be categorised into three types according to Thompson (1967): pooled interdependence – where each unit provides a discrete contribution to the whole by providing information and knowledge to the problem; sequential independence – where the current system product is dependent upon prior system output product; and reciprocal interdependence – where systems work simultaneously to produce desired results. Infrastructure interdependencies must be considered prior to design.

- *Non-ergodicity attribute:* This is commonly found in social infrastructure systems where a high degree of human influence is possible. If a conditional probability describes an individual system, it does not uniquely characterise the average or long-run behaviour of the system. For example, knowing past system states of a critical infrastructure system has no bearing on the current state or possible future infrastructure system state and events. Past elicited information may be use useful.

- *Non-holonomic attribute:* This deals with unpredictability of complex system states. Berry (1990, p.34) describes non-holonomic as "a type of nonintegrability, arising when a quantity is slaved to parameters so as to have no local rate of change when those parameters are altered, but nevertheless fails to come back to its original value

when the parameters return to their original values after being taken round a circuit." Hence, knowing past events and information about infrastructure system may not guarantee knowing next system state. This suggests a need for elicitation methods that can rapidly respond to changes.

Many other system attributes exist. However, the selected attributes serve two important purposes: First, they provide necessary information to the reader before developing the proposed framework and second, they provide a perspective on challenges for TSE approaches.

4 Nature of the system observer

This section addresses the nature of the complex system observer. The term observer is used to describe the infrastructure system owner, designer, and user. Since system requirements originate from the system observer, this section provides an in-depth discussion on the nature of the observer.

Successful design of system-to-be does not only depend on the elicitation of true infrastructure systems requirements but also on the nature of the system observer's perspective on the infrastructure. However, assuming that the world views of the observers (owner, designer, and user) are compatible can be misleading. It has been suggested that observers can perceives paradigmatic situations along the lines of ontology, epistemology, and methodology (Flood and Carson, 1993), as shown in Figure 1. Different positions on a continuum lines represented by arrows indicate possible predispositions and biases of a system observer. Flood and Carson (1993) note that ontological, epistemological, and methodological dispositions play a major role in what an observer thinks about a phenomenon (infrastructure requirement), how the investigate infrastructure requirements and how they represent knowledge regarding infrastructure and its requirements.

Figure 1   Nature of infrastructure system observer (see online version for colours)
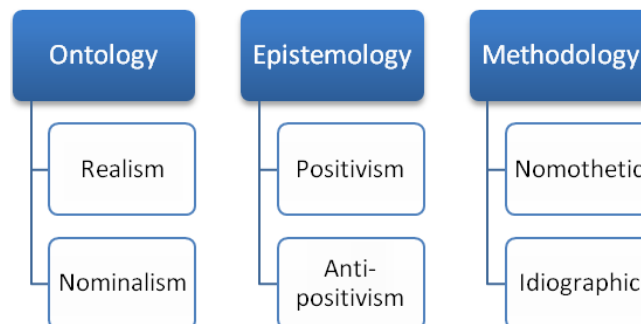
Ultimately, the resulting system is a product of the nature of the system observer. A system observer who has an objective view of the world will often view the infrastructure system and its requirements as deterministic and in turn, rely heavily on realistic, positivistic, and nomothetic approaches as opposed to a an observer with soft subjective view of the world (Flood and Carson, 1993). Therefore, the authors conclude that the

nature of the observer, the nature of system infrastructure, and the nature of the infrastructure environment are critical in the elicitation of true system requirements and the development of system-to-be. In the following section, the authors illustrate the effectiveness of a common approach in elicitation of requirements to show a need for better approaches to deal with requirements elicitation for complex systems.

5   Elicitation of requirements using 'V' model

The 'V' model was developed in 1980s by Forsberg and Mooz and has since gone through different revisions, but its applications are vast in the industry. Forsberg and Mooz (1999) note that the 'V' model is "requirements-driven, and starts with identification of user requirements. When these are understood and agreed-to, they are then placed under project control, and through decomposition, the system concepts and system specification are developed. The decomposition and definition process is repeated over and over until, ultimately, lines of code and piece parts are identified."

The level of detail for this model indicates that, it is primarily concerned with technical aspects of the system requirements. Technical requirements of system are necessary and have improved many systems (Keating et al., 2008; Blanchard and Fabrycky, 2006; Forsberg and Mooz, 1999; Blanchard, 2008). However, complex infrastructure system requirement transcend beyond technical aspects of infrastructure (Gheorghe and Vamanu, 2008; Thissen and Herder, 2003).

Table 1   Implications for using unfit approaches

Complexity attribute	Implications for the V model
Algedonic	System behaviour is not concerned the concern of the 'V' model. Traditionally, TSE approaches are not used for experimentation purposed where the initial results are used to refine system requirements in order to arrive at true system requirements. The reward after pain (in form of incurred and overrun cost) is not acceptable.
Complementarity	Consensus must be reached in order for progress to take place under the 'V' model during the elicitation of requirements. However, infrastructure problems are a topic where consensus may not be reached creating a duality type of a problem. Infrastructure system stakeholders' perspective can become irreconcilable, rending progress impossible.
Emergence	The 'V' model is ineffective in dealing with emergence because it can only capture technical elements of the system requirements. It is not intended to capture emerging system behaviour. Uncertainties in infrastructure and it environment may render the elicited requirement invalid due to emerging behaviour.

One of the major problems of applying the 'V' model to complex and dynamic situations is its inability to handle change efficiently. Forsberg and Mooz (1991) note that if a change is made in situation, then the whole project must be stopped and re-initiation should take place. Table 1 shows implications of using this model based on infrastructure system attributes.

The view presented here is also similar, albeit in different context, to van Lamsweerde (2009). Van Lamsweerde (2009) note that elicited, evaluated, specified, and

analysed requirements change because the world keeps evolving. This may seem obvious, but implications and failures associated with choosing wrong methods, tools, techniques, and approaches are enormous as indicated in Table 2.

Table 2 Systemic failures associated with unfit approaches

Complex system	Failures
Ariane 5	Due to assumed accuracy in modelling and simulation, a $500 million satellite payload was destroyed 40 seconds into takeoff (R.b.t.I. Board, 1996).
FBI Trilogy	Initiated in 2001 by the Federal Bureau of Investigation (FBI), the "Trilogy was not a success with regard to upgrading the FBI's investigative applications. Further, the project was plagued with missed milestones and escalating costs, which eventually totalled nearly $537 million" (GAO, 2006).
Industry	232 surveyed respondents spanning multiple industries (government, information technology, communications, financial, utilities and healthcare) reported a 51% unsuccessful enterprise resource planning implementation, 46% implementation was undertaken but did not produce expected results (Cortex, 2001).

6 Framework for complex system requirements

In this section, the authors propose a three-phase framework that can be used in aiding the elicitation process for infrastructure systems. The framework is structured to capture the nature of problematic situations for infrastructure system requirement design, the nature of infrastructure system observer (owner, designer, user), and the operational environment of infrastructure system, as shown in Figure 2. Applying the following phases on a continuum basis in the elicitation phase ensures that the correct requirements are elicited prior to designing:

- *Phase 1:* Understand the nature of infrastructure system observer – the ontological, epistemological, and methodological predispositions of the infrastructure system observer are considered to ensure that the problematic situation will be handled in similar manner prior to engaging in the design and analysis of infrastructure-to-be. Observers will either have a hard objective view or soft and subjective view. This has a massive impact on tools and methods for design and protection of infrastructure.

- *Phase 2:* Identify of the nature of infrastructure - this deals with assessing and classifying infrastructure as either simple or complex based on infrastructure properties and attributes. This ensures that the right methods, tools, techniques, and approaches are selected for the requirements elicitation and the design.

- *Phase 3:* Assess the nature of operating system environment – in this phase, questions such as whether the environment for the system requirements, static or dynamic, are asked. Implications of the environmental conditional on requirements and the design are asked as well. Additionally, this enables the discovery of potential tools and their evaluations for the ability to capture requirements in such a specific environment.

The common uniting ground for this framework is the role of the dynamic environment. The environment and its boundaries shape observers' perspectives of the interdependent infrastructure system and their requirements from infancy. It may sound trivial; however, since infrastructures operate in a complex and dynamic environment, the consideration for environment is critical in elicitation of infrastructure requirements, design, and overall lifecycle of infrastructures (Ashby, 1956).

It has been suggested that true system requirements will exist independent of the observer due of biases, predispositions, and paradigms (Sousa-Poza and Correa-Martinez, 2005; Ghoshal, 2005; Sousa-Poza, 2008). Therefore, this paper suggests that the elicitation of true system requirements cannot depend on the system observer alone. The nature of requirements and the dynamic environment must be considered. The proposed framework is intended to capture infrastructure requirements from three different perspectives.

Figure 2 Framework for addressing complex system requirements (see online version for colours)

7 Conclusions

Most infrastructure systems are open systems that must operate in dynamic environments and are often interconnected to other infrastructure systems to form a system-of-systems. System-of-systems such as healthcare infrastructures, are well-interconnected to provide goods and services that the public heavily depends upon. Suggesting that the elicitation of technical requirements of complex infrastructure systems can be obtained using TSE approach is a fallacy because of the nature of infrastructures, the challenging environment, and the people who depend on such infrastructure. This paper has shown that many projects have failed due to misunderstandings resulting from the nature of the requirement observers. To obtain true system requirements requires that the elicitation process should consider the system observer predispositions, the nature of infrastructure and requirements, and the nature of the operational environment. The presented framework is aimed at aiding the requirements elicitation process during the early phases

of system analysis. Authors welcome further research on the applicability of this framework practically in critical infrastructure design and protection.

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