Human Limitation as a Source of Generic System-of-Systems Properties

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The correlation between generic properties of system-of-systems and limits of the human ability to conceptualize is addressed in this paper. The presumption was that the level of complexity necessary for SoS properties to occur is related to the ability or lack of ability of the designers and operators of the system. A concept model of a multi scale framework was developed to clarify both how an observer forms a conceptualization based on the perceived reality, and what this conceptualization is constituted of. The SoS properties were then related to the framework.

1 Introduction

System-of-Systems (SoS) is term commonly used for large and complex socio-technical systems that exhibit similar characteristics. Due to the difficulty to establish a useful definition of neither complex nor large, the SoS characteristics are used as defining properties of SoS and to delimit SoS from less complex socio-technical systems. To advance the understanding of SoS as a scientific field, more knowledge is needed on *how* and *why* the SoS properties arise.

This paper was initiated by the assumption that at least some of the properties of complex systems partly arise as a result of the limitations of those working with the system, i.e. the level of complexity necessary for these characteristics to occur is related to the ability or lack of ability of the agents in the system. To test this assumption, a concept model of a multi scale framework has been set up to clarify how an observer forms a conceptualization of reality, and what a conceptualization is. The concept model was based on a multi scale definition system (Kuras 2006).

2 Generic Properties of System-of-Systems

Definitions of SoS are frequently amended with generic properties that SoS should exhibit. All generic properties of SoS are not necessarily present in all SoS, but all SoS should exhibit most of the properties. The list of properties varies depending on the set of studied systems; however, the following characteristics are in one or another form commonly found in SoS and complex system literature: *evolutionary behavior*, *self-organization*, *heterogeneity*, *emergent behavior*, and that SoS are *small-world and scale-free networks* [c.f. (Maier 1998), (Delaurentis et al. 2006), (Kuras and Bar-Yam 2003), (Bjelkemyr et al. 2007)]. The following sub-sections briefly explain each property and its relevance to SoS.

2.1 Evolutionary Behavior

Evolution is in this context seen as a “trial-and-error process of variation and natural selection of systems” (Heylighen 1997a). Similar to Darwinian natural selection, the selection here is not guided by a goal of specific intent; rather, the selection is automatic and a result of the internal or external environment. Consequently, most engineering systems are not evolutionary; partly because they are regularly encapsulated within a non-continuous life-cycle, and partly because engineering systems mainly have a hierarchical decision structure.

Most sub-systems in a SoS are non-continuous, but the SoS itself is continuously and iteratively going through all life-cycle stages. Moreover, there is no central decision maker controlling the decisions in a SoS. Unlike Darwinian evolution, “a [system] configuration can be selected or eliminated independently of the presence of other configurations” as long as configurations are not subsequent system states (Heylighen 1997a).

2.2 Self-Organization

Self-organization is similar to evolution, but where evolution takes place primarily in a system’s interface to its environment; self-organization is an internal system process that is not “being controlled by the environment or an encompassing or otherwise external system” (Heylighen 1997b). For SoS, self-organization is primarily decomposed into operational and managerial independence. Operational independence signifies that subsystems of a SoS are independent and useful in their own right. Managerial independence signifies that a system is both able to operate independently and actually is operating independently (Maier 1998).

2.3 Heterogeneity

Complex socio-technical systems consist of a multitude of dissimilar or diverse subsystems, structures and agents. This *heterogeneity* is a strong driver of system complexity, i.e. a system with heterogeneous subsystems is naturally more complex than if the subsystems were homogeneous. A system is often heterogeneous on multiple layers simultaneously, e.g. size, architecture, life-cycle, scientific area, and elementary dynamics. This increases the difficulty of modeling a SoS, and requires people from different knowledge and science domains to work side by side. As a result, new demands for communication and information handling are required, i.e. rules for interactions between the interfaces of all nodes in a system.

2.4 Emergent Behavior

Emergence is the added behaviors that arise due to the interactions between its sub-systems, and that cannot be attributed to any of the sub-systems. There are two kinds of emergence: *weak emergence*, which can be predicted by experience or extensive modeling and simulation; and *strong emergence*, in which high-level behaviors are autonomous from the systems and elements on lower levels, e.g. the autonomous relationship between neurological processes and human cognition (Bedau 1997). These two kinds are often intertwined, which creates confusion, especially regarding how emergence can be affected (Johnson 2006). Reducing weak emergence is a substantial part of engineering work, and the engineer must always prioritize between knowledge of system behavior on one hand, and time and resources on the other. Strong emergence, on the contrary, is not addressed in traditional design methods.

2.5 Small World and Scale-Free Networks

Depending on the topology of the nodes and edges in a network, different kinds of networks emerges. For SoS, two of the more interesting kinds are *small-world networks* and *scale-free networks*, both being common to a diverse set of social, information, technical, and biological networks (Newman 2003). Braha and Bar-Yam have shown that small-world and scale-free networks also exist in large-scale engineering problem-solving networks, e.g. development networks for vehicles, operating software, pharmaceutical facility, and a hospital facility (Braha and Bar-Yam 2004).

In a small-world network most nodes are not directly connected to each other, but most nodes can be reached from every other in a small number of steps. This results in that a dynamic system with small-world coupling display “enhanced signal-propagation speed, computational power, and synchronizability” (Watts and Strogatz 1998). In a scale-free network the number of edges of all nodes in the network follows a power-law distribution, i.e. while most nodes have few edges, some nodes are highly connected and function as hubs. A consequence is that scale-free networks are fault tolerant to random failure, but vulnerable to a focused attack on the hubs.

3 Multi-Scale Framework for System Conceptualization

The nest step after distinguishing a generic set of common properties of SoS is to address how and why these properties appear, and why the properties do not appear in less complex systems. The proposition in this paper is that SoS properties arise as a result of the limitations of the human ability, i.e. the human brain is not capable to contain and process everything that is necessary to develop and operate a SoS, at least not with the traditional tools and methods that are currently used.

To address this proposition, a framework based on Kuras' effort to establish a multi scale definition of a system that is equally suitable for all kinds of systems has been used to model how humans conceptualize a system (Kuras 2006). The framework is based around the trinity of the *observer*, *reality*, and *conceptualization*. The main concepts have been extracted and related to each other in a concept model (figure 1). The sections below address both the substance of a conceptualization and the process of conceptualizing.

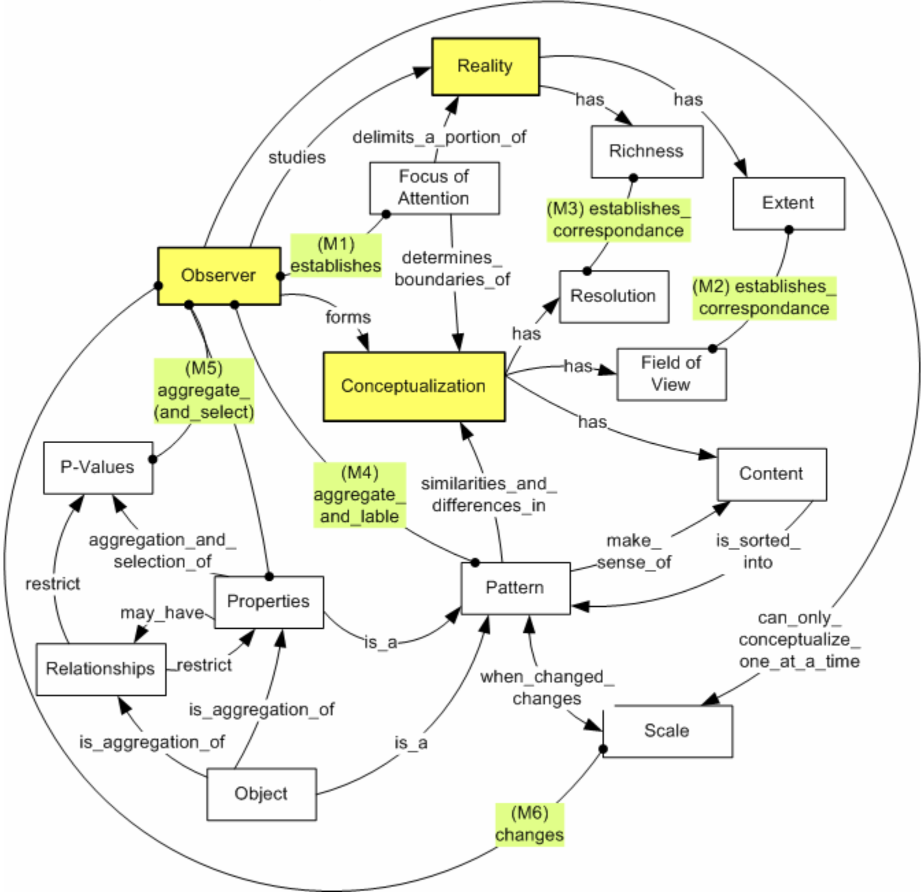

Figure. 1: Concept model of a multi scale framework, based on (Kuras 2006).

3.1 The Substance of a Conceptualization

The *observer* studies the *reality* and forms a *conceptualization*, which is based on but distinct from the *reality*. The *reality* has both an *extent*, i.e. "the immeasurable expanse of the reality” and a *richness*, i.e. “uncountable details that might be found anywhere in that expanse” (Kuras 2006).

The *conceptualization* that the *observer* forms after studying the *reality* has in itself three attributes:

- *Field of view*: the expanse of the conceptualization (c.f. *extent*)
- *Resolution*: the degree to which a part of the conceptualization can be distinguished (c.f. *richness*)
- *Content*: the substance of the conceptualization; similar to pixels.

Due to limitations to the observer’s abilities, the *resolution* and *field of view* are linked and may restrict each other. After having increased the *resolution* to a certain degree, the *field of view* must be reduced in order to further continue increasing the *resolution*. The coordinates beyond this limit, are impossible for humans to conceptualize. In order for an *observer* to make sense of a *conceptualization* of *reality*, the *observer* sorts the *content* into *patterns*, i.e. “similarities and differences that we recognize in a conceptualization”. Depending on the *content*, *field of view*, and *resolution*, different *patterns* will appear.

There are three kinds of *patterns*: object, property, and aggregation. *Objects* are nouns, e.g. brick, car, or forest. The *objects* are aggregations of both *properties* and *relationships*. *Properties* are the characteristics of the *objects*, e.g. color, shape, and velocity. Each *property* is an aggregation and a selection of *p-values*, e.g. yellow, **green**, brown, and white. The *relationships* restrict the *properties* and the *p-values*.

The concept *scale* is defined as the “level of detail visible to an observer of a system” (Bar-Yam 2002). It is used for when the current set of *patterns* is changed, i.e. some *patterns* are lost and some are gained. An *observer* is only able to conceptualize one *scale* at a time; consequently, the *observer* is unable to think about the *patterns* that have been lost unless the *observer* returns to the previous *scale*. A very simple example of this feature is a so called bi-stable figure, see figure 2.

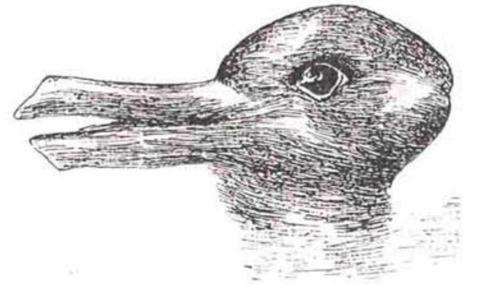

Figure. 2: Bi-stable figure of Rabbit/Duck (Jastrow 1899)

A system is conceptualized by one or many observers. The system only uses a limited set of all possible *patterns*, the rest belong to the system’s environment. The system is in it self built up by parts and subsystems, for which the system is part of the environment. A result of an *observer’s* ability to only conceptualize one *scale*, the whole system can not be conceptualized unless all necessary *patterns* can fit within one *scale*. Otherwise, the *observer* must change *focus of attention*, altering *patterns* and *scale*.

3.2 The Process of Conceptualizing

To be aware of the limitations of a *conceptualization*, it is necessary to understand how it is formed, i.e. the *modality* of a *conceptualization*. Kuras' has identified six varieties (labeled M1-M6 and shown as boxed arrows in figure 1) (Kuras 2006):

1. Establishing *focus of attention*, i.e. the delimitation of a portion of the *reality*, and determination of the scope of the *conceptualization*.
2. Establishing the correlation between *extent* and *field of view*.
3. Establishing the correlation between *richness* and *resolution*.
4. Aggregating and labeling the *patterns* of a conceptualization.
5. Aggregating and selecting the *properties* and *p-values*.
6. Altering the *scale* of a conceptualization.

All *conceptualizations* are affected by all the above *modalities*, so an *observer's* ability to conceptualize a system is the combined result of all six *modalities*.

4 Correlation between Modalities and SoS Properties

In the following sections, SoS properties are individually correlated with the, for that property, most important modalities in the framework.

4.1 Evolutionary Behavior

In an evolving system, the interface to the environment is changing in a positive direction over time, through distributed decisions and actions. To be able to conceptualize an evolving system, a new *focus of attention* must continuously be reestablished (M1). This change will in time result in changes to all other properties of a *conceptualization*, which consequently is affected by all modalities (M1-6).

It is not feasible for one *observer* to conceptualize all the necessary transformations in the evolution of a SoS; accordingly, the *conceptualizations* of multiple agents are required to fully capture the evolution of a SoS. That is, this human inability delimits the possibility for central decision making, and a decentralizes SoS organizations. Evolution is consequently not a direct result of an observer's inability to conceptualize; evolutionary behavior is rather a result of internal and external system changes.

4.2 Self-Organization

As described in the previous section, human inability delimits the possibility for central decision making. Consequently, self-organization is a direct result of human limitations in forming a *conceptualization*. Most obviously, humans are unable to simultaneously achieve a satisfactory *resolution* and *field of view* (M1) when a system increases in size and complexity. Together with the inability to conceptualize multiple *scales* (M6), this results in a conceptualization that can not capture enough of the studied system. By allowing self-organization through local decision making, more *field of view*/*resolution* coordinates and scales can be conceptualized more realistically.

4.3 Heterogeneity

Observers of a heterogeneous system face the difficulty of simultaneously aggregating and labeling a diverse and numerous set of *patterns* to make sense of the *content* (M4). As a consequence, aggregation and selection of *properties* and *p-values* also become difficult (M5). An effect of the inability to aggregate and label *patterns* is that multiple *scales* are needed to capture heterogeneous systems (M6). Heterogeneity is however not a result of human inability, it is an inevitable property of SoS. The problems associated with heterogeneity are nevertheless caused by this inability.

4.4 Emergent Behavior

Both strong and weak emergent properties are consequences of the discrepancy between the *reality* and the *conceptualization*, and are therefore a direct result of our inability to conceptualize adequately. Inability to execute each and every modality results in potential emergent behavior (M1-M6). Reduction of weak emergence requires improvements of our ability to simultaneously carry out all modalities. In addition to this, strong emergence also requires an improved ability to individually carry out each modality.

4.5 Small World and Scale-Free Networks

Small-world and scale-free networks are the result of the network properties a*verage path length*, *clustering coefficient*, and *degree distribution*. That is, correlation between this SoS property and our ability to conceptualize requires correlation with the network properties. Since systems of diverse size and complexity exhibit small-world and scale-free characteristics, it confirms that size and complexity do not affect network properties. An increased ability to conceptualize would therefore not greatly affect the structure of a network.

4 Conclusions

The ability to conceptualize is essential for planning, development, and operation of a system. It is therefore necessary to understand the building blocks of a conceptualization, and how these are affected by the person forming it. The presented framework has provided a foundation to advance the knowledge of both what a conceptualization is and how it is formed.

Out of the selected set of generic SoS properties, self-organization and emergent behavior are closely related to the modalities, i.e. how a conceptualization is formed. The other three are not caused by our ability to conceptualize; instead, evolutionary behavior and network properties are enabling system functionality, and heterogeneity is an inevitable property of socio-technical systems. Nevertheless, the problems associated with SoS properties would in many cases be less cumbersome had our ability to carry out the modalities been improved.

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