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FRAMEWORK TO INVESTIGATE EMERGENCE IN SYSTEM ENGINEERING

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ABSTRACT

System Engineering is the process of identifying, implementing and maintaining solutions to real world problems. Some problems tend to be messy with no single solution or set of effective and accurate requirements, often resulting in implementation failure. Emergence is a characteristic of complex systems and occurs when multitudes of elements interact with each other and the environment to give rise to behavior at a higher level that could not easily be deduced. This paper proposes a framework for identifying and investigating emergent behavior as part of the Complex System Engineering process through modeling and simulation.

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1. INTRODUCTION

The aim of System Engineering (SE) is to solve problems. Until recently most engineering problems could be isolated and solved separately. However, due to the dramatic increase in integration of systems, compounded by communications technology advances, this is not easily achieved anymore. The traditional SE techniques need to be adapted to cope with the increasingly complex world. Gleizes [1] states that there is an exponential growth in the complexity of systems because of the following characteristics:

a. Large number of different elements per system.
b. The distribution of knowledge and control of these elements.
c. The presence of non-linear processes.
d. Systems being open systems and the environment being dynamic and unpredictable.

According to Sheard [2] [3], up to now systems engineers have been focusing on harnessing the “order” within systems and a new focus is required on the “chaos” aspects. SE is finding it difficult to develop complex interoperating and software-intensive systems within the current budget and time scales. Therefore, complexity is one of the current focus areas in the field of SE to develop Complex System Engineering (CSE) related techniques and processes.

Ryan [5] noted that the systems approach to complex systems lacks a clear understanding of emergence. Emergence is one aspect of complex systems that can be harnessed by CSE to create a better understanding of the problem space as well the implications of possible solutions. It is the aim of this paper to propose a framework to guide the investigation of emergent properties through modeling and simulation as part of the CSE process.

This paper will focus on the phenomenon of emergence and its role within SE as it starts off with explanation and definitions of SE and CSE. It is followed by a discussion of emergence, with the focus on typical characteristics. This will lead to the introduction of the scientific method, which is adopted into a general CSE process. The prominence of iterative modeling and simulation will be highlighted as the crux of the methodology.

2. SYSTEM ENGINEERING

2.1 System Engineering Defined

Stepney [6] summarized engineering as a careful arrangement of components in a specific way to achieve high level properties or functions. The important aspects are the design and development processes to ensure that the parts are correctly assembled for dependable and safe implementation of the system. According to Fromm [7] this is achieved through the application of established scientific knowledge. Natural sciences such as physics, chemistry and biology use experiments to gather data to validate or prove hypotheses and theories, being the basis of the “Scientific Method”. Therefore, engineering as well as SE is actually based on the foundation of the scientific method.

SE had its origin in scientific attempts, through Systems Thinking, to cater for increasing complexity in development projects in the middle of the previous century. As the complexity of systems is continuously increasing, SE must also continue to develop new techniques to keep abreast of the demands. The wider implications and influences of developed systems are considered more and more when specifying requirements. This includes the sustainability, supportability and acceptance of the system in the wider environment. As a result, the simplest of systems can become an element in a wider and "complex" system of systems, especially where the roles and cognitive interactions of humans are considered.

INCOSE [8] defines System Engineering as:

"… an interdisciplinary approach and means to enable the realization of successful systems".

SE is described as the discipline of designing and application of a whole (system) that is distinct from its parts. This process includes assessing the problem as a whole and considering all the known factors having an influence (social and technical). SE is applied as an iterative process of top-down synthesis, development and operation of a real world system to satisfy the requirements of a user. The focus is on Systems Thinking, which is a perspective on reality and how the parts within the wholes (systems) interact. Modeling and simulation is a well-used technique in SE at various levels. It is often applied to test designs for functionality, suitability and trade-offs.

From the discussion above it seems that INCOSE recognizes the role of complexity, non-linear processes (interactions) and emergence in SE. An iterative process should be used to detect the actual requirements and emergent properties within a system. Since complexity may lead to unexpected and unpredicted behavior, the aim is to minimize undesirable consequences through cross discipline engineering. Unfortunately, SE became bogged down is a myriad of rigid standards and processes as a replacement for Systems Thinking. This necessitates a fresh look at how to approach real life and complex problems.

2.2 Complex System Engineering

Fromm [7] reiterated that when engineering complex systems, science is used to explain and to understand complexity while engineering attempts to hide and master it. Engineering attempts to hide complexity behind a simple interface by first predicting and then trying to understand the amount of unpredictability. The aim of CSE is to understand the complex system before it can be specified and realized. According to Gleizes [1], Fromm [7] and INCOSE [8] complex systems contain the following:

a. Many components that can operate independently as individual systems and even have different life cycles.
b. Distributed knowledge and control.
c. Non-linearity within the systems as well as in the interactions between them.
d. Different operational layers of elements or subsystems.
e. An open system within a dynamic environment.
f. A vast range of stakeholders, such as public, client, construction team, operators, designers, financiers, government, opposing forces
g. Subsystems or elements may change or evolve over time

Because of complexity, designers and engineers can never have a "perfect knowledge" of the system and the environment that are part of the problem and solution. Johnson [9] discriminates between complex systems and complicated systems by the presence of emergent properties. They may have beneficial (e.g. support unintended uses) or detrimental (e.g. undermine safety requirements) effects on the implementation of the solution system. A combination of top-down and bottom-up approach is required to assess a system in both static and dynamic aspects. This is required to understand a system in terms of its parts and the interactions between them.

Just by observing the problem and trying to implement solutions will also, in effect, change the problem space. This “problem space” is defined by the complex emergent properties. The possible outcomes cannot be predicted by an individual, even with a thorough understanding of the parts of the complex system and its environment. The current, or traditional, SE methodologies want to control the functions and quality in order to provide a solution to a perceived problem. Emergence may not be controllable. There must be a balance between allowing the system to be resilient and adaptable through emergence while ensuring it stays fit for the high level requirement. Describing systems that exhibit emergent behavior completely in a bottom-up approach with simple models is virtually impossible. The modeling and simulation techniques currently used by SE may not be suited to analyzing complex scenarios. A fresh approach, such as Agent Based Modeling (ABM) may be required for complex environments where the inputs and interactions are not linear.

Johnson [9] agrees that a thorough understanding is required of the relationship between the system as a whole and its parts, as well as the possible emergent properties to ensure an effective and efficient design. Wicked and messy problems may cause system designs to have unintended, and possibly fatal, consequences. The market demands an ever increasing product value and functionality so that manufacturers follow a path of continuous improvement. Therefore, they deliver more features, innovation and better looking products. Coping with the resultant design complexity, while still achieving time-to-market and profitability goals, is the real challenge for (system) engineering.

3. THEORY OF EMERGENCE

3.1 Emergence Defined

One of the earliest definitions of emergence is from Aristotle, as quoted by Stepney [6], who stated that:

> *“Things which have several parts and in which the totality is not, as it were, a mere heap, but the whole is something beside the parts”.*

This is nowadays phrased as the

> *“Whole is more than the sum of its parts.”*

Everyday life, from nature to the internet, is full of examples of emergent behavior. A few examples are:

a. Nature and living systems. Ant colonies, bees, termites.
b. Non Living Emergence. Color, friction, patterned ground, weather.
c. Organizational Systems. Economics, political processes, combat, traffic patterns, cities, World Wide Web, Internet, Artificial Intelligence and language.
d. Technological Systems. Autopilot systems, robotics, integration and interoperability.

Fromm [7] defines emergence as the distinction between the properties of the low level components and the global or high level patterns visible to the observer. Emergence is what happens at the boundary between the system and its elements. It is emphasized through a bottom-up process with the appearance of new or novel structures at a higher level. This is echoed by Ryan [5], Johnson [9] and Stepney [6] who agrees that a complex system has emergent properties if it consistently presents characteristics in a macro-state that is not present in the microstate. The emergent behavior of a system cannot be predicted from looking at individual elements in isolation. This may even lead to novel behavior of the system, which may be a surprise to the observers of the system. The observed high level novel behavior is a result of the nonlinear interactions between the elements and/or the environment.

According to Gleizes [1] incidents are caused by unforeseen interactions between operators and systems that could not have been anticipated using current engineering techniques. Beneficial emergent properties are the adaption of a product by users for applications never intended by the designers. Emergent behavior can also be harmful such as the undermining of safe usage of a system and unforeseen catastrophes, such as the Uberlingen air disaster and 2003 North American blackout. Had emergence been investigated within these systems, catastrophe could have been averted.

Fromm [7] lists the advantages and disadvantages of systems that are embracing emergence instead of ignoring it as the following:

a. Advantages and Positive Properties. Robustness, adaptiveness, fault-tolerance, scalability, concurrency, adaptability, flexibility, low brittleness.
b. Negative Properties and Drawbacks. Low predictability and understand-ability, controlling (emergent) behavior is difficult, engineering design is hard, accidents and errors possible, restricted reliability for computational purposes.

3.2 Characteristics of Emergence

During analysis of complex systems, the observation of any level of emergence can be useful as long as it can be modeled and understood. Ronald [10] proposed a test for identification and recognition of emergence. It consists of the three steps “Design”, “Observation” and “Surprise”. In essence, a specific language is used to describe or design a system of elements at local level. A different language is used to describe the observed global behavior. The difference between the two languages used constitutes a surprise. The level of the surprise will determine the level of the emergence observed. Stepney [6] and Ryan [5] list the following characteristics for emergence:

a. Equilibrium. The system operates at a state far from equilibrium as there is a continuous flow of matter, energy and information through it. The system is open and utilizes material from the environment for the patterns of its existence.
b. Levels. The system has different levels operating simultaneously with different length- and timescales.
c. Language. Different languages are used to describe the low-level and high-level systems.
d. Irreducibility. Emergent properties are irreducible. The properties of the complex whole cannot be deduced from a complete knowledge of the elements or combinations thereof.
e. Scope. The scope is defined as the set of components within the boundary of the system existing between the associated system and its environment.
f. Resolution. Resolution refers to the finest spatial distinction between two alternative system configurations. The greater the resolution, the greater the possible number of possible outcomes.

Bedau [11] and Johnson [9] proposed the idea of classification of emergence ranging from weak to strong. Weak emergence presents where the macroscopic behavior can be derived through modeling of the microscopic behavior and other reductionist (bottom-up) techniques. This requires a set of initial conditions and the rules of interactions with each other and the environment for a starting point for the simulations. Strong emergence consists of higher-level behaviors that are autonomous from the underlying microscopic layers with a high level of novelty. It is almost impossible to replicate high macroscopic behavior traditional modeling and simulation techniques. Strong emergence requires more specialized modeling techniques such as ABM to try and understand the underlying rules.

4. CAPTURING EMERGENCE

4.1 System Design

As seen from the discussions above, emergence is a characteristic of complex systems that can be used to assist development of solutions. Emergence is observed when a model of the complex system consists of local rules, actions and interactions that do not describe the global phenomena completely. Nowadays, most of the system's elements, or concepts thereof, already exist and requires integration into a System of Systems (SoS). The exact global behavior of the SoS, as a result of the elements operating together under environmental conditions, may not yet be known. The nonlinear inputs, especially from social and cognitive humans, may cause unanticipated emergent behavior of the total system.

The most important step is to identify when additional or different SE procedures and techniques are required, while not merely relying on standardized processes. The emergence must be recognized and captured to assist in defining the requirements and local rules. This is where transformation from Traditional SE to CSE takes place. Emergent behavior cannot necessarily be controlled; however a system designer wants control over the system, aiming to achieve the required functions of his system in a predictable and singular fashion.

A complex system or SoS must be designed to be resilient and adaptive to overcome a dynamic environment and openness. This can be achieved through self-organization, which is the process of change without external control or inputs. It follows that to design a complex system or SoS, the rules that make the system achieve the desired and useful emergent behavior are required. The knowledge of this set of rules will go a long way in analyzing the problem to start defining the requirements of the solution. The development process should include modeling and simulation to develop an understanding of possible outcomes. One possible approach is to apply the Scientific Method to the artificial world of modeling and simulation instead of the natural world.

4.2 The Scientific Method

Fromm [7] states that one way to investigate Complex Systems for emergent behavior is the “Scientific Method”, as seen in Figure 1. The word “Science” is related to Latin word Scientia, meaning knowledge and actually refers to a system of acquiring knowledge. In the natural world the basic element of knowledge is a theory, metaphor or model. However, in the artificial world of complex systems, represented through agent based models, the basic unit of knowledge is a combination of simple local rules and complex global behavior. The ultimate objective is to find the rules of the game.

The scientific method consists of repeated cycles of observation of phenomena, deriving a hypothesis to make predictions under certain conditions and to test. This in turn will lead to more observations to change or improve the hypothesis to make further prediction to be tested. After a number of these cycles the hypothesis should converge to a theory that holds for all stated and tested conditions. The power of this method lies in maintaining tight control over the cycles. This methodology can be applied when investigating the behavior of agents in complex systems through simulation and observing emergence.

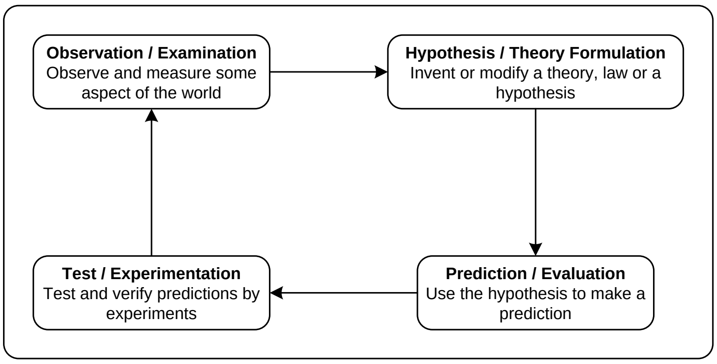

Figure 1: Basic Scientific Method

Success in the application of the scientific method is determined by how the experiments are planned and set up as well as the development of the models. The core of the problem must be addressed and the recorded data carefully analyzed. Computer modeling and simulation provides a virtual laboratory to investigate and analyze certain phenomena.

4.3 Emergence in Complex System Assessment Framework

The framework for the analysis of Emergence in Complex Systems, as seen in Figure 2, is derived from combining the “Scientific Method” and the method proposed by Fromm [7] and De Wolf [12]. They proposed a Two Way approach, Top-Down combined with Bottom-Up, for the assessment and analysis of complex systems. In the Top-Down cycle the high level requirements are analyzed and delineated. The operational context and expected scenarios are defined from the initial high level requirements, within which the system are to operate successfully. From these the required roles, tasks and functions of the system are derived. The result of the Top-Down cycle is the Goals, States and Interactions of all the elements or subsystems within the total system. These will provide the parameters for the Simulation and Synthesis during the Bottom-Up cycle of the development process. The operational and interaction rules are applied to the different agents within the system. The ABM simulation results and possible, often surprising, emergent properties are analyzed and compared to the initial stated requirements. Discrepancies are to be scrutinized for possible changes in the initial requirements or operational rules of the low level agents.

The high level Top-Down and Bottom-Up processes are implemented by means of a Scientific Method as seen in the centre portion of Figure 2 with more detailed steps. The exact execution of the different steps is to be tailored as required by the specific environment. Applying this in the iterative fashion of the scientific method will ensure refinement of the models (agents) and the associated parameters or rules. The process must ensure that the models that hold true for the observed behavior by testing. The models are then used to predict and test behavior under extreme circumstances. Outcomes of the assessment cycles are used to improve models and learn more about the problem. The techniques used for Modeling and simulation must be able to pick up the weak signals, which may cause serious problems or advantages in our systems under a specific set of conditions.

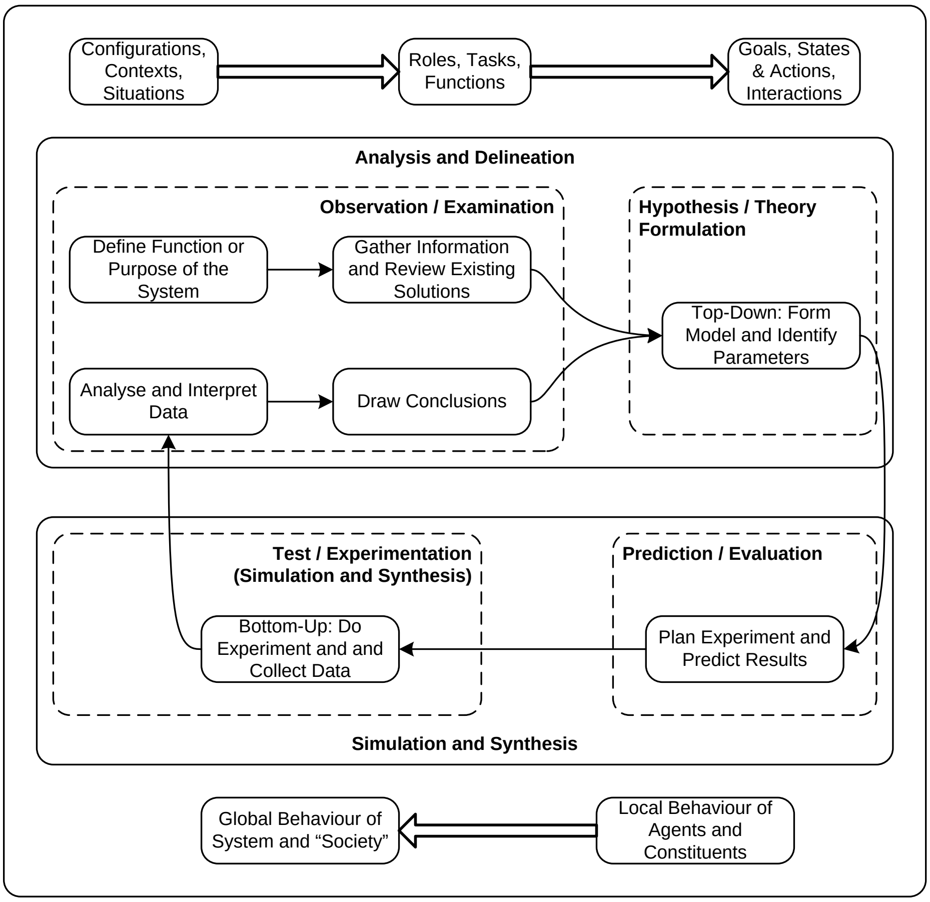

Figure 2: Framework for Analysis of Emergence in Complex Systems

The validation of models and verification of results is crucial to the Modeling and Simulation process. ABM is a technique that will be useful in simulating emergent behavior in the complex system. Real life experiments must be carefully planned and set up to verify at least certain aspects of the models. Even if the models are not perfect, they should still point to the critical aspects of the complex environment to analyze in detail. At the very least the modeling and simulation process should highlight what is not known about the system, problem or environment.

5. CONCLUSION

Systems must be designed with some resilience built in to successfully survive in complex environments. In many cases, applying rigid traditional System Engineering techniques and processes fall short in absorbing the intricacies of complex environments. It is very dangerous to supplement Systems Thinking with standards and processes.

Emergent behavior is a relevant dimension for System Engineering, especially when attempting to solve complex problems. The problem to be solved and the total system environment must be analyzed to identify possible emergent behavior. Detecting emergent behavior is a useful pointer to the requirement for more flexible SE or CSE techniques in development of a solution. This output phenomenon can then be utilized to capture the essence or basic rules governing the required solution.

The process of building the knowledge base of the problem and environment must follow a strict scientific process that employs different methods of modeling and simulation. CSE must have a strong focus on modeling and simulation for identifying and analysis of emergent behavior. The proposed framework is the basis for detailed investigations into the application of ABM in the domain of CSE.

6. REFERENCES

[1] **Gleizes, M, Camps, V, Georgé, J, Capera, D.** 2008. Engineering Systems which Generate Emergent Functionalities, *Engineering Environment-Mediated Multi-Agent Systems, Lecture Notes in Computer Science*, Volume 5049/2008, pp58-75.

[2] **Sheard, S, A, Mostashari, A.** 2009. Principles of Complex Systems for Systems Engineering, *Systems Engineering*, Volume 12, Issue 4, pp 295–311.

[3] **Sheard, S, A**. 2006. Bridging Systems Engineering and Complex Systems Sciences, *The International Conference on Complex Systems*, www.necsi.org.

[4] **Cooper, D, R, Schindler, P, S.** 2000. *Business Research Methods*, 7th Edition, McGraw Hill International Edition, Statistics and Probability series.

[5] **Ryan, A**. 2006. Emergence is coupled to scope, not level, *Cornell University Library*, Wiley, 2006.

[6] **Stepney, S, Polack, F.A.C, Turner, H.R.** 2006. Engineering Emergence, *11th IEEE International Conference on Engineering of Complex Computer Systems*.

[7] **Fromm, J.** 2006. On Engineering and Emergence, Distributed Systems Group, Kassel University, *eprint arXiv:nlin/0601002*.

[8] **INCOSE**. 2010. *Systems Engineering Handbook,* v3.2, INCOSE-TP-2003-002-03.2.

[9] **Johnson, C.W.** 2006. What are emergent properties and how do they affect the engineering of complex systems?, *Reliability Engineering & System Safety - RELIAB ENG SYST SAFETY* , vol. 91, no. 12, pp. 1475-1481.

[10] **Ronald, E.M.A, Sipper, M, Capcarrère, M.S.** 1999. Design, Observation, Surprise! A Test of Emergence, *Artificial Life*, Vol. 5, No. 3, Pages 225-239.

[11] **Bedau, M, A.** 1999. Weak Emergence, *Noûs*, Volume 31, Issue Supplement s11, pages 375–399.

[12] **De Wolf, T, Holvoet, T, Samaey, G.** 2006. Development of Self-organizing Emergent Applications with Simulation-Based Numerical Analysis, *Engineering Self-Organising Systems, Lecture Notes in Computer Science*, 2006, Volume 3910/2006, 138-152.

[13] **Polack, F, Stepney, S**. 2005. Emergent Properties Do Not Refine, Department of Computer Science, *Electronic Notes in Theoretical Computer Science*, Volume 137, Issue 2, 21 July 2005, Pages 163-181.

[14] **Fromm, J.** 2005. Ten Questions about Emergence, Distributed Systems Group, Kassel University, *eprint arXiv:nlin/ 0509049*.