Synergy of Systems Engineering and Modeling and Simulation

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Abstract

The shift of paradigm in modeling and simulation studies of large and complex systems, namely synergy of M&S and systems engineering is explained.

1. INTRODUCTION

We are witnessing an important paradigm shift in simulation of large and complex systems. This paradigm shift is taking advantage of the synergy of modeling and simulation (M&S) and systems engineering (SE) which has a common characteristic: they are not an end by themselves. However, they are vital in solving real and important problems. M&S is applicable to simple as well as to complex and large scale system problems, including systems of system problems. SE is applied to moderate to very complex and large scale system problems. M&S and SE are mutually beneficial. Even in the 1960s, M&S was very useful in SE by providing virtual labs to study system problems. There are many cases, especially in the studies of large and complex systems where M&S is vital for the success of the project; however, ignoring SE in such projects may be detrimental to the success of the project. Hence, several institutions active in the deployment of complex and large scale systems started to have groups jointly active in SE and M&S. SE is also very useful in areas other than M&S, such as software engineering as software systems engineering, even though SE and software engineering are distinct disciplines. Similarly, it appears that time is ripe for a closer synergy of SE and M&S to solve complex and large scale system problems. This may lead to simulation systems engineering (SSE) while still keeping both SE and M&S as distinct disciplines.

The article covers the following: Section 2 provides a review of some pertinent aspects of M&S; this includes scope and perspectives of M&S, importance of M&S and associated responsibilities, increasing complexity of both M&S systems and M&S applications, and life cycle of M&S. Section 3 is on systems engineering and covers definitions of systems and systems engineering, SE tasks and life cycle, and highlights of role of SE in some disciplines. Section 4 is on synergy of M&S and SE, and includes M&S for Se, SE for M&S, and M&S and SE. Section 5 is for conclusions. Extensive references are given and the appendix covers the essential tasks of systems engineering.

2. Modeling and Simulation (M&S)

M&S, as a discipline, is vital for the success of many applications areas in a multitude of disciplines (Ören 2002a). In this article, due to space limitation, we focus on the scope of M&S, importance of M&S and associated responsibilities, and especially on the increasing complexity of both M&S systems and M&S applications which leads to the requirements of the synergy of SE and M&S. The subsection on the M&S life cycle is provided to draw the parallels between the life cycle of M&S and the major tasks of systems engineering. More references on different aspects of M&S can be found at the website of the Body of Knowledge of M&S (M&SBOK) which is being developed under the auspices of the National Training and Simulation Association (NTSA).

2.1 Scope of M&S

M&S has many facets; often specialists in one area have a tendency to ignore other aspects. At one extreme this leads the point of view of "Anything other than war is simulation" (STRICOM). Of course, this point of view stressing on the main task is understandable; however it does not allow a top-down decomposition of the elements of a simulation system to be able to develop advanced simulation environments and applications. Most probably due to this type of view, the importance of contributions of simulation to science and engineering, known to practitioners for several decades, is rediscovered recently (NSF 2006). However, this is a very good indicator of the acceptance of the value of M&S from another perspective.

Simulation is used for two categories of applications: (1) to gain experience (simulation in training) with the following types of usages: live, virtual, and constructive simulations and (2) to perform experiments (simulation in areas other than training). Simulation can also be perceived as (1) an infrastructure to support real-world activities, a computational activity, a model-based activity, a knowledge-generation activity, and a knowledge-processing activity. A detailed view of the many aspects and different perceptions of M&S are given at the site of the M&SBOK project at (M&SBOK-aspects).

2.2 Importance of M&S and Associated Responsibilities

Simulation is used for many important application areas. Some of them and the associated responsibilities are documented in two separate articles (Ören 2002b, 2005c).

2.3 Increasing Complexity of both M&S Systems and M&S Applications

Complexity is a pervading phenomenon in natural, social, business, artificial, engineered or hybrid systems. Cells, organisms, the ecosystem, markets, societies, governments, cities, regions, countries, large scale software and hardware systems, the Internet, all are examples of complex systems. Scientists use various forms of measurements and models to explore, understand, and elucidate the characteristics of such systems, while engineers build and design working artificial complex systems. As the engineered phenomena become more and more complex, we are observing a convergence as engineers try to model the systems in an attempt to analyze them. However, there is another trend that makes these models extremely complex.

Complexity research mainly happens at the borders between various disciplines and thrives on interactions between engineering and the sciences. Predictive modeling comes from the context of theoretical science, with a bias toward deductive reasoning and a resulting preference for validity as a standard quality (Bankes 1999). The current trend in M&S treats the use of computer models as experimental science. In this new era, the purpose of M&S in dealing with complexity is not necessarily to predict the outcome of a system, rather it is to reveal and understand the complex and aggregate system behaviors that emerge from the interactions of the various individuals involved (Yilmaz 2006). This viewpoint is based on the observation that emergent engineering applications are becoming dynamic, adaptive and open systems (Little 2005), for which the tools of traditional closed systems viewpoint are limited. More specifically, it is suggested in (Little 2005) that if our critical infrastructures are to continue to provide vital services safely and reliably, the linkages between people, organizations, and technology need to be fully understood and managed holistically. As we start exploring the state space of such systems, the types of M&S applications, as espoused in this paper, will gradually increase and find their place within the engineering domain.

2.4 M&S Life Cycle

The life cycle of simulation model development is depicted in Figure 1. The stages of the life cycle are shown as solid rectangles. The model development as well as validation processes that relate the phases of the life cycle are shown as arrows. The solid arrows denote the model development processes, while the dashed arrows indicate verification and validation processes.

The problem domain analysis starts with the system entity or problem situation. System analysts create abstractions on the system structure and behavior to derive system theories and properties of interest. If system data exists due to experimentation with the system, the analysts generalize and hypothesize from the results to facilitate the derivation of the formulated problem definition. Balci (1994) provides in depth characterization of these phases. The solution domain entails the formulation of the simulation requirements and objectives, model formulation through analysis and conceptualization, model specification and implementation, experimentation, and revision. Each of these phases is briefly discussed below.

2.4.1 Requirements and Simulation Objectives Formulation

Requirements formulation process takes formulated problem definition as input to generate simulation objectives and requirements definition. The goal is to bridge the gap between system level objectives definition and simulation model domain. The process is usually divided into three areas of effort: (1) problem recognition, (2) evaluation and synthesis, (3) simulation context (domain) modeling. It is important to understand modeling in a system context. This requires reviewing the model scope in such a way that credible problem recognition is ensured. The objective is recognition of the basic problem entities as perceived by the customer/sponsor. During the evaluation and synthesis the analyst must define all externally observable entities, evaluate the content and flow of information as well as processes to establish the simulation context.

2.4.2 Simulation Model Conceptualization

The goal of simulation model conceptualization is to derive a simulation conceptual model. Simulation conceptual model is defined by Pace (1999) as the simulation developer's way of translating model objectives into a detailed analysis and design framework. The framework defined by (Pace 1999) characterizes the simulation concept and provides a basis from which the software, hardware, networks, and systems that will make up the simulation can be built. The simulation concept includes the representation of the mission space as well as the simulation space. All solution domain elements and specification of how they are expected to interact constitute the mission space. The simulation space part of the simulation concept includes all additional functional and operational capabilities and elements to explain how the simulation will meet its objectives. The steps of the conceptual model development can be characterized as follows: (1) collecting authoritative information, constraints, assumptions regarding the simulation context from the simulation objectives and requirements; (2) characterizing the simulation mission space entities and processes; (3) determining and representing simulation elements constituting the simulation concept space that realizes the entities and processes of the mission space; and (4) specifying the interactions and relationships among the simulation elements.

2.4.3 Simulation Model Specification and Design

Model specification and design process entails the translation of the conceptual model into a detailed simulation software design model. The simulation software design can be represented by using a variety of paradigms and model representation methodologies such as structured methods, object-oriented modeling languages (i.e., UML, OMT), flowcharts, activity diagrams, condition specification (Overstreet and Nance 1985). It is essential to choose an appropriate modeling paradigm for the application domain and the simulation conceptual model identified during the earlier phases of the life cycle.

2.4.4 Simulation Model Implementation

Simulation model implementation is a programming or construction (i.e., model composition) process in which the model specification (design) is translated into an executable simulation. The programmed model in the life cycle denotes the executable simulation developed either with existing simulation packages (i.e., SIMSCRIPT, GPSS, MODSIM III, SIMULA, JDEVS, and SIGMA) or high-level languages. Programming simulations with high-level programming languages requires understanding of conceptual frameworks (i.e., worldviews) of simulations. Event scheduling, activity scanning, and process interaction are the major worldviews with which model implementors need to be familiar. The choice of programming paradigm (i.e., object-oriented, procedural, object-based) has implications on the V&V process as well.

2.4.5 Experimentation and Revision

Simulation is performed to conduct experiments for the purpose of understanding the behavior of systems and evaluating their alternative operation strategies. This requires collecting the desired information from model execution and interpreting the results for decision making. Model developers need to be aware of experiment design methods to make valid inferences and collect information with minimal cost.

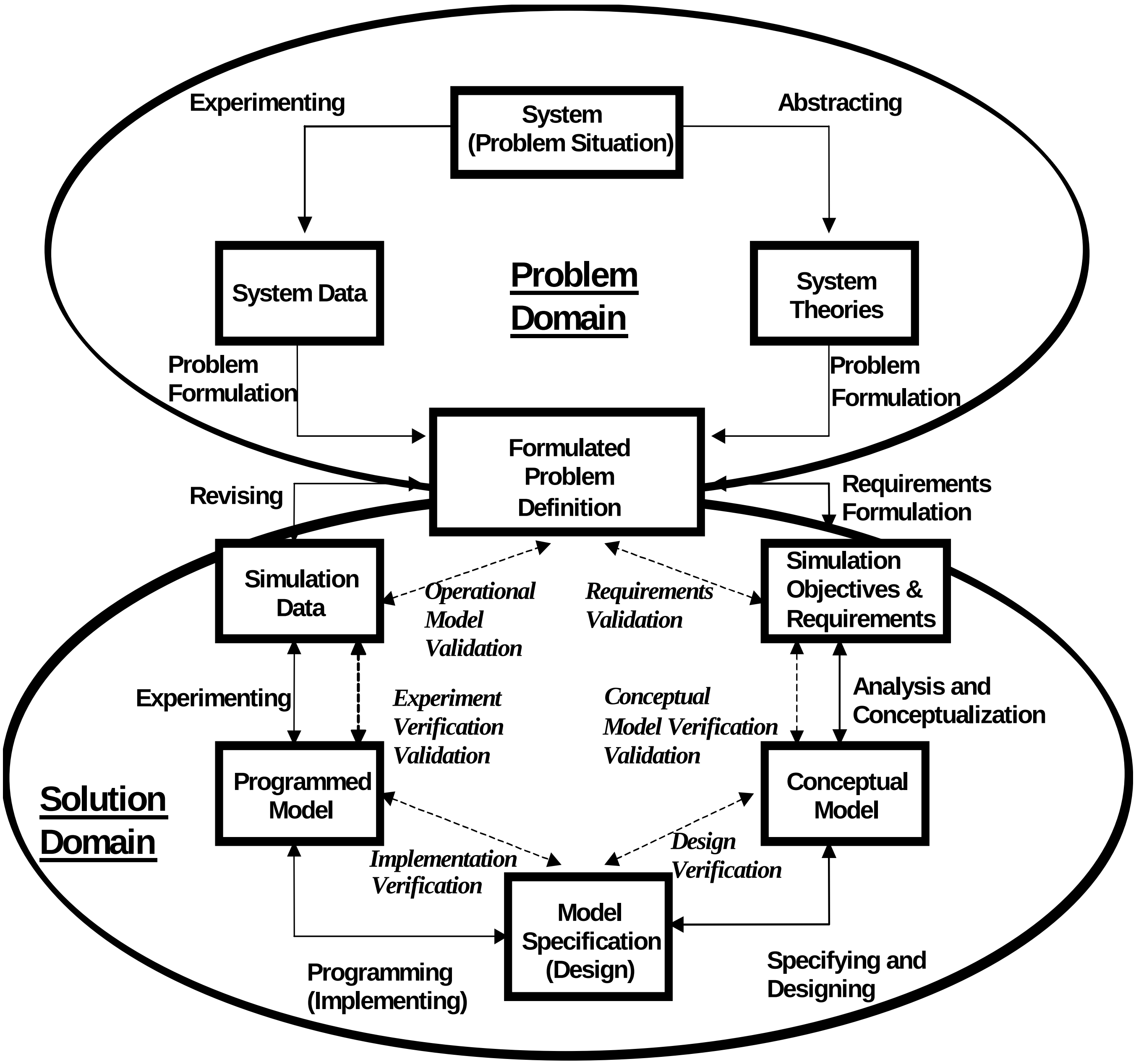

Figure 1: Simulation Modeling Lifecycle

3. SYSTEMS ENGINEERING (SE)

3.1 Definitions

3.1.1 System

"A system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behavior and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected (Rechtin, 2000)" (INCOSE-fellows)

3.1.2 Systems Engineering

"Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle.

This process is usually comprised of the following seven tasks: **S**tate the problem, **I**nvestigate alternatives, **M**odel the system, **I**ntegrate, **L**aunch the system, **A**ssess performance, and **R**e-evaluate.

These functions can be summarized with the acronym SIMILAR: **S**tate, **I**nvestigate, **M**odel, **I**ntegrate, **L**aunch, **A**ssess and **R**e-evaluate. ... It is important to note that the Systems Engineering Process is not sequential. The functions are performed in a parallel and iterative manner" (INCOSE-fellows).

3.2 SE Tasks

The details of the six major tasks of systems engineering are given by the fellows of INCOSE (INCOSE-fellows).

3.3 SE Life Cycle

Several views exist as the major tasks in systems engineering. Figure 2 is the one recommended by the fellows of International Council on Systems Engineering INCOSE (INCOSE-fellows). Another view is called "V".

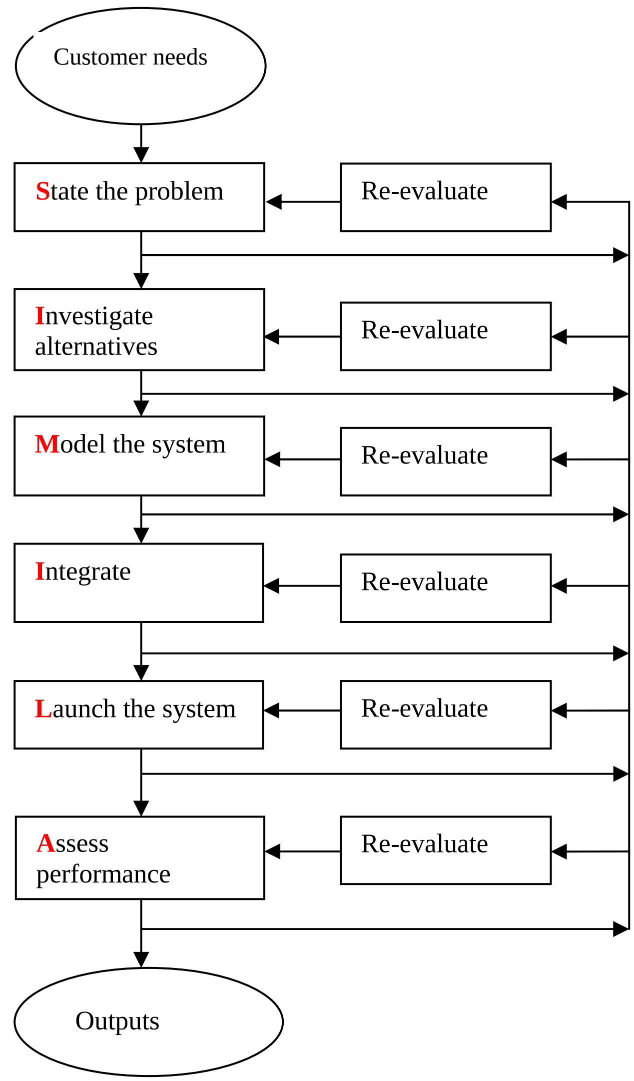

Figure 2. Systems Engineering Process (adopted from INCOSE-fellows; originally from Bahill and Gissing 1998)

3.4 Role of SE in Some Disciplines

Disciplines dealing with complex and large scale systems benefit from the synergy with systems engineering. Such disciplines include: integration industry (Zittel 2001), test (Stuckey 2005), software engineering, and program management. In a presentation, as part of technical challenges and solutions, the following was reported: Challenge: "Software team lacked systems engineering domain knowledge" (VSIL).

4. SYNERGY OF M&S AND SE

References on M&S and SE can be found at the references section of the M&SBOK project (SE and M&S).

4.1 Modeling and Simulation for Systems Engineering

M&S provides ideal laboratory facilities for SE studies to perform experiments with system models. Use of M&S within systems engineering enhances systems engineering with experimentation abilities and has been used for decades (Smith 1962).

The use of M&S in SE is well established. The mission of the M&S Committee of NDIA's Systems Engineering Division is for example: "Advance the understanding and use of modeling and simulation in the practice of systems engineering for DOD. programs" (Hollenbach 2003, NDIA-M&S Com).

Connors et al. refer to simulation-based systems engineering to life-cycle management of defense systems (Connors et al. 2002).

Stuckey (2005) reports inherent value of M&S in systems engineering and test in defense applications and also points out to some common M&S failings.

4.2 Systems Engineering for Modeling and Simulation

One of the three recommendations made by Hollenbach to overcome some shortcomings of M&S in important applications is to "Adopt Disciplined M&S Planning (Left Side of Systems Engineering "V" for M&S)" (Hollenbach 2003). Important details can be found in the reference.

Another reported shortcoming is: "Zeolots oversell M&S, don't state model assumptions, limitations & uncertainties." For this and similar shortcomings of M&S with or without SE, the impediment would be to assure that the contractors adopt the Code of Ethics for Simulation Professionals and monitor any violations (SimEthics).

Bartolomei (2001) develops a framework for the use of SE in M&S within a military acquisition program.

The term "simulation systems engineering" and more specialized versions of it are already in use. For example, MITRE refers to Distributed Simulation Systems Engineering (MITRE 2001).

An action item to improve M&S in the Acquisition M&S Master Plan is "COTS Systems Engineering Tools" (AMSMP 2006).

4.3 M&S and SE

M&S and SE are distinct disciplines. However, in large and complex system problems, both can benefit from their synergy. Hence, SE can benefit from M&S, by having experimentation facilities. Similarly, M&S can benefit from a systematic approach of the major tasks of SE. Hence, regardless of the terminology used, large and complex system studies require and benefit from the use of both SE and M&S approaches, methodologies, and techniques. National Institute of Aerospace has, for example, a center named "Center for Aerospace Systems Engineering, Modeling and Simulation" with the following mandate: "A systems engineering modeling and simulation lab is being developed to integrate systems engineering practices across the complete system of life-cycle to develop system requirements, access design and technology alternatives, and operate the system virtually to determine the best design based on cost, safety, performance, and risk." (NIA)

Similarly, the University of Alabama in Huntsville has a center named "Rotorcraft Systems Engineering and Simulation Center" (RSESC).

5. CONCLUSION

As a result of the advancements, M&S is applied to more and more complex and large scale systems and M&S systems also are becoming more complex. This double complexity requires a higher level of problem solving paradigm in M&S studies. Systems engineering provides such high level paradigm to solve problems. Hence, already some institutions responsible for the deployment of solutions to large and complex problems started to benefit from the synergy of modeling and simulation and systems engineering. In this article, highlights of this paradigm shift are outlined.

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