Overview of Modeling and Simulation of Complex Systems

Introduction

Systems and enterprises are an integrated composition of elements or sub systems that provide a capability to satisfy a stated need or objective. These integrated elements can be products of hardware and software, people, facilities and procedures. To develop a system or enterprise successfully you must first define the problem that exists, identify the mission requirements (or business drivers) of the organization(s) needing the problem to be solved, evaluate high-level concepts for solving the problem, select the concept that makes the most sense in light of the mission requirements, develop an operational concept around the selected concept, create system-level requirements, create architectures and derived requirements for the subsystems, components, and configuration items consistent with the decomposition of the system, design the integration and test process for the parts of the system, conduct the integration and test process for the parts of the system, manufacture/assemble the parts of the system, deploy the system, train operators and maintainers, operate/maintain the system, refine the system, and finally retire the system. Simulation cuts across all of the phases of the life cycle. Simulation plays a key role in system/enterprise development activities must be brought to bear on the development system, manufacturing system, deployment system, training system, maintenance system, refinement system, and retirement system throughout the life cycle.

The use of modeling and simulation (M&S) is expanding dramatically in all aspects of design and optimization in both traditional engineering (civil, mechanical, electrical, etc) and non-traditional engineering (systems engineering, engineering management, etc) and business. Logistics, inventory management, project management, combat simulation modeling, training, and many more elements of assessing risk, material development, cost estimation, prediction, training, etc., are all analyzed using M&S. As complexity increases of interoperability, systems requirements, and the number of physical components, the role of simulation continues to increase in all phases of the life cycle.

Commercial firms incorporate M&S into all phases of the development of new products, covering the entire life cycle from concept development to sustainment. The military[1] has used M&S for many years because it can provide a realistic, and cheaper, ways to train and conduct analysis of complex material and force structure analysis. Specifically, M&S can be used (1) to evaluate requirements for new systems and equipment; (2) to conduct research, development and analysis activities; (3) to develop digitized prototypes and avoid the building of costly full scale mockups; and (4) to plan for efficient production and sustainment of the new systems and equipment.

Because M&S has become a catchall term for all aspects of computer based analysis and is very domain dependent we need to start with some basic terms and points of discussion:

A **model** is a physical, mathematical or logical representation of a system, entity, phenomenon, or process. There is no movement in a model. Think of a plastic replica of an airplane or a car, or a mathematical equation that predicts the probability of an event occurring.

[1] Some of this text was copied from http://www.education.dmso.mil/ms_primer.asp?a=s4&b=view&c1=272 April 20, 2005.

A **simulation** is the implementation of a model over time. It shows how the model works. It is a technique used for design, testing, analysis, or training, where a model can represent “real world” systems or concepts. A simulation moves. You can see the model(s) in the simulation moving—whether it shows military units moving across a battlefield or engine parts moving in a simulated car engine. M&S provides virtual duplication of products and processes, and represents those products or processes in readily available and operationally valid environments. Use of such models and simulations can reduce the cost and risk of “life cycle” activities.

When discussing realism, we must define two basic terms—fidelity and resolution. Cost is a factor as realism can be expensive in terms of resources needed for development and computing power.

Fidelity is the degree to which aspects of the real world are represented in M&S. It is the foundation for development of the model and subsequent VV&A. Fidelity is a measure of how the model or simulation acts. Does it act like the real thing?

Resolution is the degree to which physical (appearance) aspects of the real world would be represented. Resolution is a measure of how the model or simulation looks. Does it look like the real thing?

Cost is a serious issue in terms of both fidelity and resolution. Both require money and computing power. The key is to require only what is needed to do the job. Te appropriate degree of resolution is always a challenge when building an M&S. Most M&Ss are developed at finer degree of fidelity that the data available and that can reasonably be validated, verified, and accredited (VV&A).

The Department of Defense (DoD) has established three classes of simulations - virtual, constructive, and live and are defined as:

Virtual simulations represent systems both physically and electronically. Think of a video game or a cockpit mockup used to train pilots--these are virtual simulations.

Constructive simulations represent systems and their employment through the use of extensive, complex mathematical and decision-based modules and statistical techniques. A constructive simulation is a computer program. The user inputs data to cause an event to occur then gets the results. For example, a military user may input data on a military unit telling it to move and to engage an enemy target. The constructive simulation determines the speed of movement, the effect of the engagement with the enemy, and any battle damage that may occur. Results can be provided digitally or visually, depending on the type of simulation used.

Live simulations are simulated operations conducted by real operators using real equipment. Military training events using real equipment are live simulations. They are considered simulations because these events are not conducted against a live enemy.

Ways to Study a System

When we conduct the analysis of a component, sub-system, system, etc., there are many ways to analyze it as shown in Figure 1.1

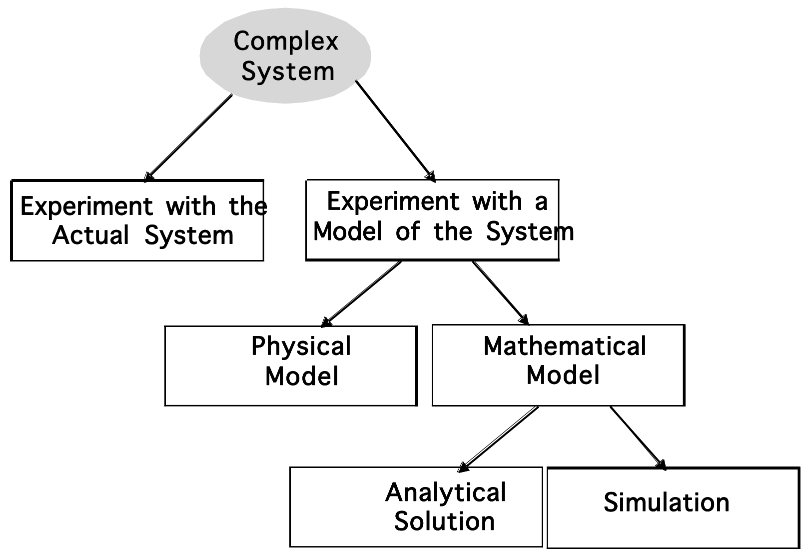

Figure 1.1 Ways to study a System[2]

Experiment with the Actual System

Obviously building a prototype and testing it in actual field trials is the desired – but certainly not the most cost effective – to develop a new system. Conducting "what if" analysis and large enterprise wide solutions can only be conducted in a synthetic environment. From the simplest component to modern airplanes, detailed models are developed and simulated under a wide variety of conditions. Only then, are prototypes build and some actual tests conducted.

Physical Modeling

Before the advent of cheap computing, must engineering analysis was conducted used physical models. As shown in Figure 1.2, even complex systems were modeled using physical models. Even today, physical models are still used in the design and testing up to the system level.

[2] Taken from Simulation Modeling and Analysis by Averill M. Law, 4th Edition, McGraw Hill, 2006.

Figure 1.2 A physical model of the lower Mississippi River at the Waterways Experiment Station[3]

Mathematical Modeling

A mathematical model is an abstract model that uses mathematical language to describe the behavior of a system. Figure 1.3 shows he results of an analytical model that represents the behavior of a tire in snow. This finite element model would be termed an M&S by someone in the mechanical engineering profession.

[3] Taken from http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=PHYSICALMODELS!37, July 31, 2006

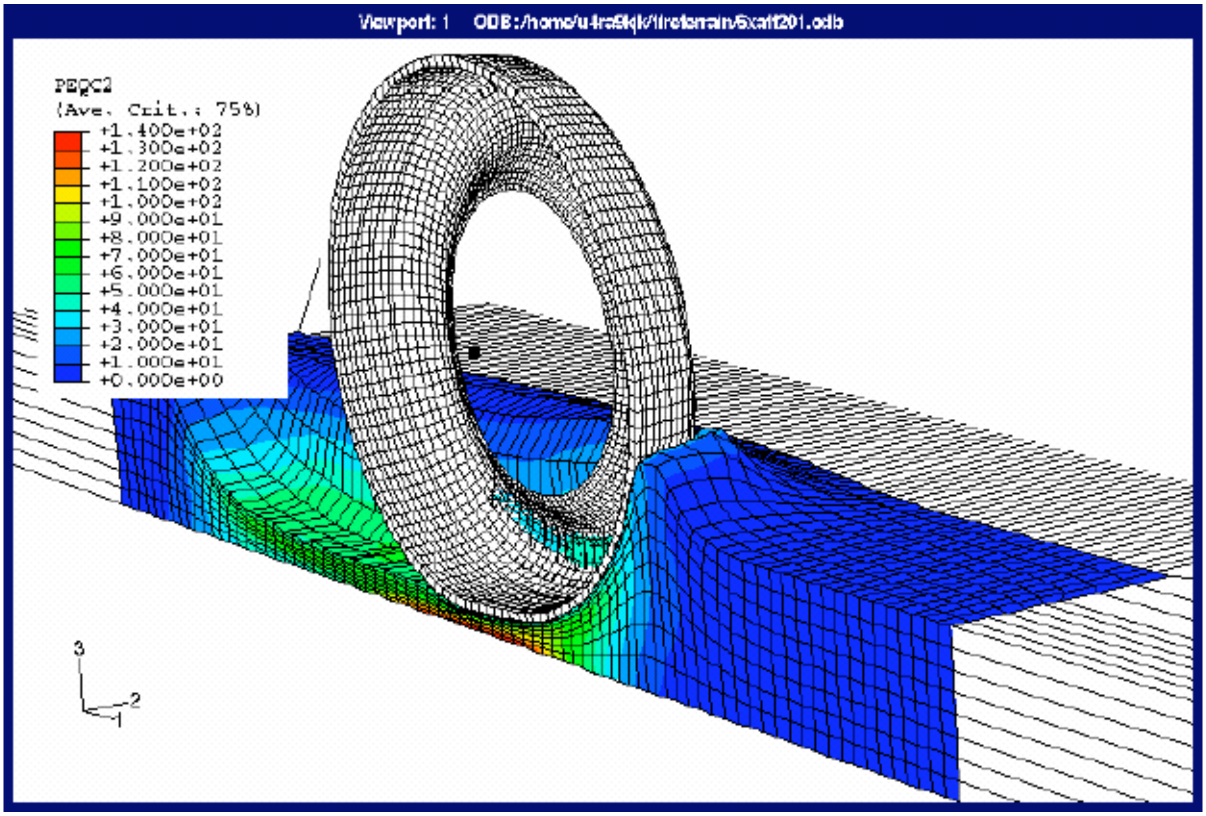

Figure 1.3 Finite element model of a tire rolling through snow[4]

Mathematical models can be classified in several ways, some of which are described below[5].

1. Linear vs. nonlinear: Mathematical models are usually composed by variables, which are abstractions of quantities of interest in the described systems, and operators that act on these variables, which can be algebraic operators, functions, differential operators, etc. If all the operators in a mathematical model present linearity, the resulting mathematical model is defined as linear. A model is considered to be nonlinear otherwise. In a mathematical programming model, if the objective functions and constraints are represented entirely by linear equations, then the model is regarded as a linear model. If one or more of the objective functions or constraints are represented with a nonlinear equation, then the model is known as a nonlinear model.
2. Deterministic vs. probabilistic (stochastic): A deterministic model is one in which every set of variable states is uniquely determined by parameters in the model and by sets of previous states of these variables. Therefore, deterministic models perform the same way for a given set of initial conditions. Conversely, in a stochastic model, randomness is present, and variable states are not described by unique values, but rather by probability distributions.
3. Static vs. dynamic: A static model does not account for the element of time, while a dynamic model does. Dynamic models typically are represented with

[4] Taken from http://www.crrel.usace.army.mil/ard/Finite_Element_Modeling_of_Tires.pdf accessed July 31, 2006.

[5] Taken from http://en.wikipedia.org/wiki/Mathematical_model#Classifying_mathematical_models accessed May 15, 2007.

difference equations or differential equations.

4. Lumped parameters vs. distributed parameters: If the model is homogeneous (consistent state throughout the entire system) the parameters are lumped. If the model is heterogeneous (varying state within the system), then the parameters are distributed. Distributed parameters are typically represented with partial differential equations.

The Role of M&S and Systems Engineering

System Engineering Environment

Systems engineering was born in the telecommunications industry of the 1940s and nurtured by the challenges of WW II, when project managers and chief engineers with the assistance of key subsystem leads oversaw the development of aircraft, ships, etc. The post-WWII creation of more complex systems—e.g., ballistic missiles, communication systems—led to the formalization of SE as an engineering discipline. The development teams, especially for large weapons systems, employed thousands of engineers requiring the use of formal methods to integrate subsystems into useful and reliable systems. Today the profession of SE is fairly well evolved, producing systems that meet the customer's requirements. Modeling and simulation plays a key role throughout the life cycle of a product.

Yet, as impressive as those early triumphs and the evolution of SE as a profession, the complexity of systems that humans choose to build, manage and control continues to grow at an accelerating rate, with no sign of letting up – outpacing our ability as engineers to develop processes and tools to manage their development. Today's engineered systems are more complex than their predecessors, not only in the sophistication of elements from which they are constructed, but in the number and nature of the interconnections between the elements. System failures today, whether an automobile malfunction on a busy highway or loss of a spacecraft on a distant planet, are more likely to result from an unanticipated interaction between elements than from the failure of a single part. Software-intensive systems represent a special challenge because of the myriad of possible logic paths that can be woven through their code. And as Moore's law continues to drive down the size of computers and drive up their speed and capability, functionality that was once deeply embedded in the physical configuration of components has begun to emerge as software, enabling collaboration between components that would have been unimaginable only a few years ago.

Before we can develop a definition for SE, we must develop a taxonomy for what constitutes a system and the hierarchical nature of the elements of any complex system. Table 1.1 shows the hierarchical nature of what constitutes a system. Depending upon ones perspective, a system can be loosely used to describe everything from a part to a system of systems (SoS). The following definitions of succeeding levels of the systems hierarchy are necessary for understanding the role of SE.

Table 1.1 Hierarchical role of systems

System of Systems[6]	A SoS is defined as a configuration of systems in which component systems can be added/removed during use; each providing useful services in its own right; and each is managed for those services. Yet, together they exhibit synergistic, transcendent capability.
System[7]	An integrated set of elements, segments, and/or subsystems that accomplish a defined objective such as an air transportation system.
Subsystem	An integrated set of assemblies, components, and parts which performs a clearly separate function, involving similar technical skills, or a separate supplier. Examples are aircraft on-board communications subsystem of an airport of an airport control tower as a subsystem of the air transportation system.
Assembly	An integrated set of components and/or subassemblies that comprise a defined part of a subsystem, e.g., the pilots radar display console on the fuel injection assembly of the aircraft propulsion subsystem.
Subassembly	An integrated set of components and/or parts that comprise a well-defined portion of an assembly, e.g., a video display with its related integrated circuitry of a pilot's radio headset.
Component	Comprised of multiple parts; a clearly identified item, e.g., a cathode ray tube or the ear piece of the pilot's headset.
Part	The lowest level of separately identified items, e.g., a bolt to hold a console in place.

Unfortunately, SE has many definitions ranging from high-level statements to detailed process overviews and with all being appropriate depending upon one's background and perspective. Most accepted definitions have common themes describing a top-down process, which is life-cycle oriented, and involves the integration of functions, activities, and organizations (Blanchard and Fabrycky, 2006).

Most definitions can be classed as high-level or detailed trying to capture the essential elements of SE. The most widely accepted definitions of SE are presented in Table 1.2.

[6] AFSAB (Air Force Scientific Advisory Board), 2005. System-of-Systems Engineering for Air Force Capability Development. SAB-TR-05-04. July. Available online at http://stinet.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA442612. Last accessed on April 2, 2007.

[7] INCOSE (International Council on Systems Engineering), 2004. INCOSE Systems Engineering Handbook (Version 2A), June.

Table 1.2 Standard definitions of systems engineering

INCOSE	SE is an interdisciplinary approach and means to enable the realization of successful systems
Wikipedia	SE is an interdisciplinary approach and means for enabling the realization and deployment of successful systems. It can be viewed as the application of engineering techniques to the engineering of systems, as well as the application of a systems approach to engineering efforts. Systems Engineering integrates other disciplines and specialty groups into a team effort, forming a structured development process that proceeds from concept to production to operation and disposal. Systems Engineering considers both the business and the technical needs of all customers, with the goal of providing a quality product that meets the user needs.
Military Standard on Engineering Management (499A)[8]	The application of scientific and engineering efforts to: (1) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (2) integrate related technical parameters and ensure compatibility of all related, functional, and program interfaces in a manner that optimizes the total system definition and design; (3) integrate reliability, maintainability, safety, survivability, human, and other such factors into the total technical engineering effort to meet cost, schedule, and technical performance objectives.
Department of Defense	An approach to translate approved operational needs and requirements into operationally suitable blocks of systems. The approach shall consist of a top-down, iterative process of requirements analysis, functional analysis, and allocation, design synthesis and verification, and system analysis and control. SE shall permeate design, manufacturing, test and evaluation, and support of the product. SE principles shall influence the balance between performance, risk, cost, and schedule.
NASA	SE is a robust approach to the design, creation, and operation of systems.

All of these definitions are appropriate depending upon the reader's perspective. In order to capture all the essential elements addressed in this report we choose a fairly developed and detailed definition of SE to represent our work. We define SE[9] as the translation of a need or deficiency into a system architecture through the iterative process of functional analysis, allocation, implementation, optimization, test, and evaluation; the incorporation of all technical parameters to assure compatibility between physical and functional interfaces, hardware and software interfaces, in a manner that optimizes system definition and design; and the integration of performance, manufacturing, reliability, maintainability, supportability, global flexibility, scaleability, interoperability, upgradeability and other specialties into the overall engineering efforts."

Or simply stated SE is the translation of a need into a system's architecture through an iterative process that results in an operationally effective system design. Figure 1.4 shows an important relationship between the functional decomposition shown in the center, supportability and logistics shown on the right, and cost shown on the left. As you follow each process flow, activities across each type of requirement are interdependent on and impact each other. This figure demonstrates the importance of trade-off analysis in developing system requirements in order to balance performance, cost, and other specialties along the system life cycle.

[8]Military Standard on Engineering Management (499A). Available online at http://www.product-lifecycle-management.com/download/MIL-STD-499A.pdf. Last accessed on April 2, 2007.

[9]Modified from SDOE 625 Class Note – Systems Design and Operational Effectiveness, Stevens Institute of Technology, 2007.

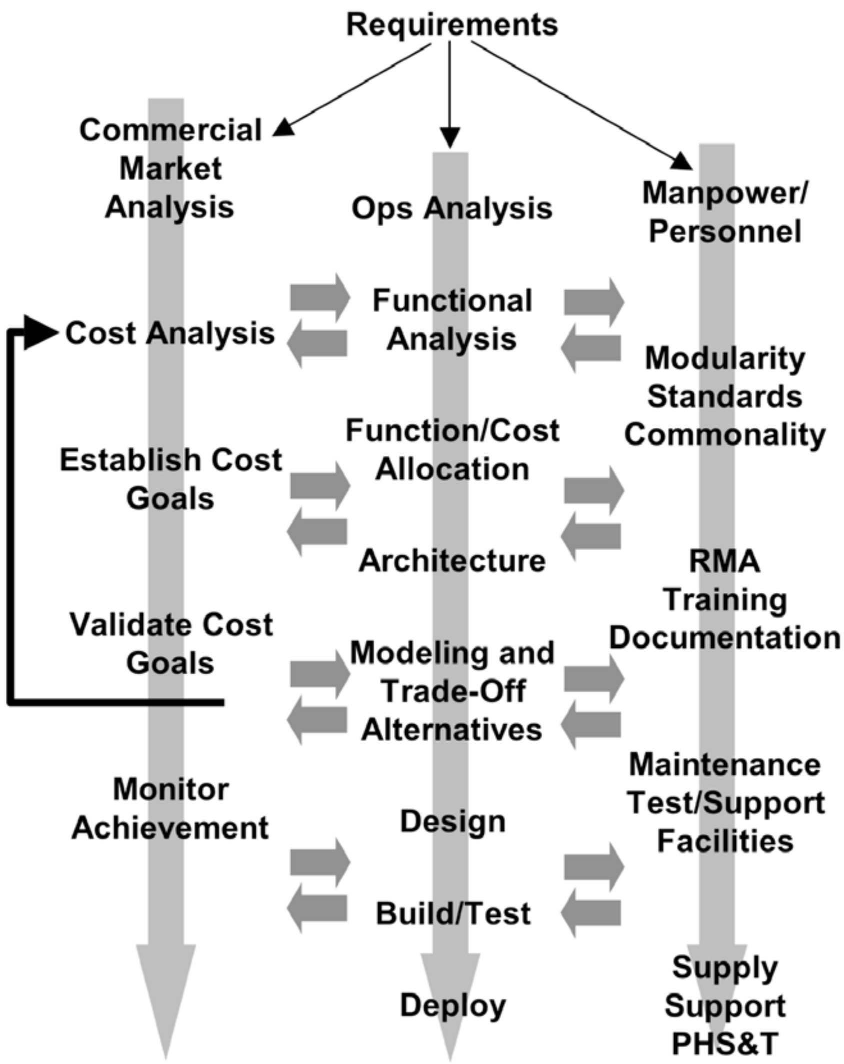

Figure 1.4 Relationship between the traditional SE functions (center column), cost (left column), and supportability and logistics (right column)[10]

Systems engineering goes well beyond traditional engineering concepts and tools. In the broadest sense, SE encompasses systems thinking and other related systems disciplines inherent to the execution of traditional SE. Systems engineering is not solely intended for those products described in the academic definition of a system but should also include subsystems, systems of systems, enterprise level problems, etc. Systems engineering should be applied to financial, risk, political, requirements development, social, etc., and all other related areas needed to build a system.

[10] Modified from SDOE 625 Class Notes for Systems Design and Operational Effectiveness, Stevens Institute of Technology, 2007.

Fundamental to the application of good SE is an understanding of the systems life cycle. There are many frameworks used to characterized SE efforts. A structure process is key to developing large complex systems. Probably the most common illustration of the SE framework is the "Vee" model shown in Figure 1.5.

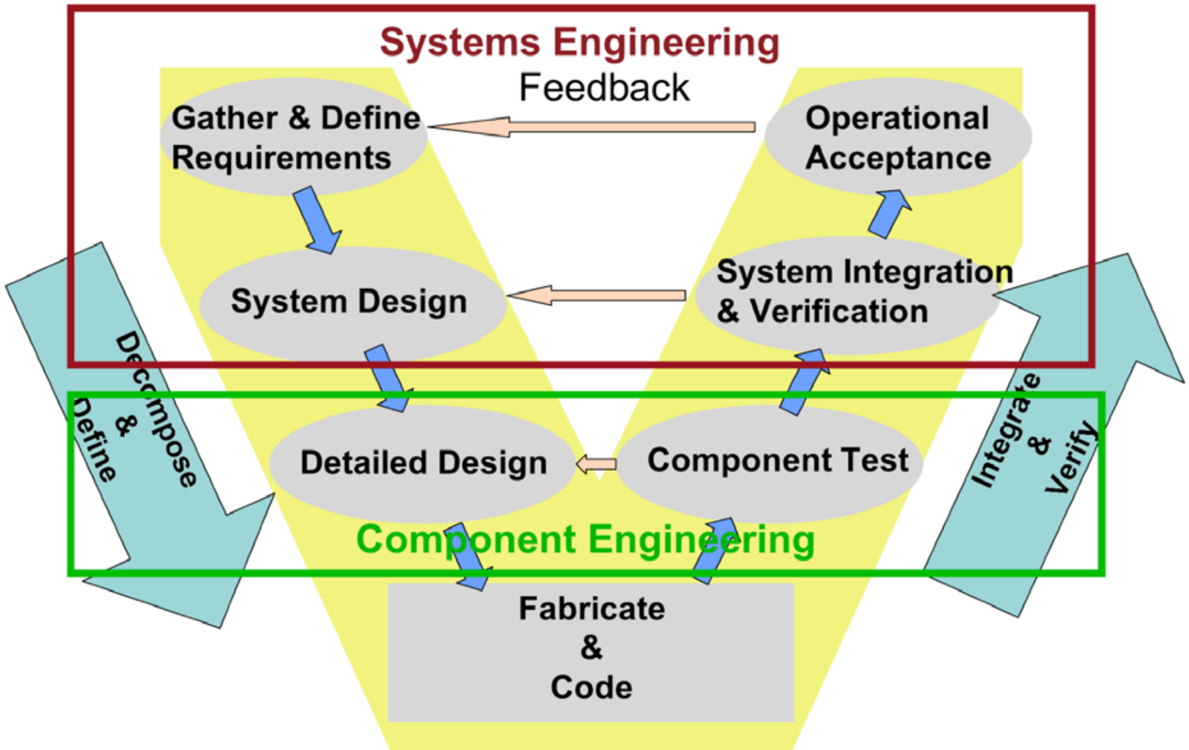

Figure 1.5 The Vee model systems engineering.[11]

The main product of good SE is robust and efficient architectures. Architectures are multi-dimensional representations or combinations of "What, How, Where Who, When, and Why". Regardless of perspective, method, source data, and framework, an architecture description is a representation of a defined domain in terms of its component parts, what those parts do, how the parts relate to each other, and the rules and constraints under which the parts function. It is important to note the difference between an architecture *description* and an architecture *implementatio*n. An architecture description is a representation or "blueprint" of a current or postulated "real-world" configuration of resources, rules, and relationships and generally contains "views" that are meaningful to each of the multiple disciplines involved in the implementation of the system. Once the blueprint enters the design, development, and acquisition process, the architecture description is then transformed into a real *implementation* of capabilities and assets in the field. An architecture framework provides guidance on describing architectures, but requires other tools in the toolset to move from representation to implementation of capabilities and assets.

As stated by Blanchard and Fabrycky (2006)[12], "systems engineering is good engineering with certain designated area of emphasis, a few of which are noted as follows:

[11] The VEE model is generally attributed to the National Aeronautics and Space Administration [NASA] who in 1988 saw a benefit in bending the Waterfall model into the "V" shape for software development.
[12] Blanchard, Benjamin and Fabrycky, Wolter, 2006. Systems Engineering and Analysis (4th Edition). Prentice Hall International Series in Industrial and Systems Engineering.

1. A top down approach is required viewing the system as a whole. Although engineering activities in the past have very adequately covered the design of various system components, the necessary overview and an understanding of how these components effectively fit together has not always been present.
2. A life-cycle orientation is required, addressing all phases to include system design and development, production and/or construction, distribution operation, sustaining maintenance and support, and retirement and material phase-out. Emphasis in the past has been placed primarily on system design activities, with little consideration given to their impact on production, operations, support, and disposal.
3. A better and more complete effort is required relative to initial identification of system requirements, relating these requirements to specific design goals, the development of appropriate design criteria, and the follow-on analysis to ensure the effectiveness of early decision making in the design process (Blanchard and Fabrycky, 2006).

An interdisciplinary effort (or team approach) is required throughout the system design and development process to ensure that all design objectives are met in an effective manner. This necessitates a complete understanding of the many different design disciplines and their interrelationships.

Modeling and simulation are two different discplines that are often lumped together into an all encompassing term. Figure 1.6 shows has modeling and simulation are applied across all the areas of interest for the systems engineer or engineering manager.

Table 1.3 shows some common software packages and how they might be applied to the problems that typical would be encountered by engineering and scientists working in systems engineering, engineering management, or are interested un large enterprise problems.

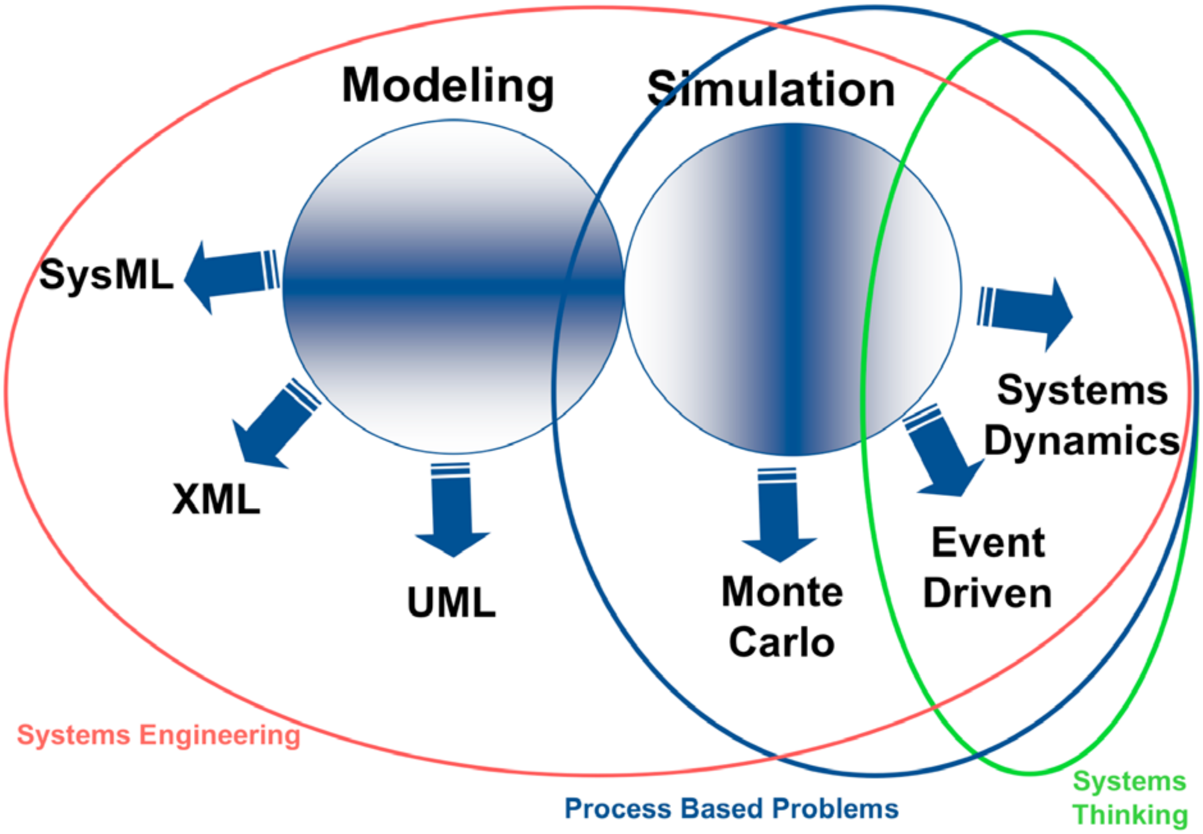

Figure 1.6 Role of Modeling and Simulation in systems engineering and engineering management

Table 1.3 a) The role of M&S in systems engineering

Type of Modeling and Simulation	Software
Systems Dynamics (SD)	VESIM, Systemigram, PET, AnyLogic, Stella
Monte Carlo (MC)	Matlab, SPSS
Event Driven (ED)	Arena, CORESim, GPSS, SLAM, ProModel, Prosim
High Resolution (HR)	Finite Element Analysis, First Principal

b) Appropriate level of analysis as a function of M&S type

Level	Types of Modeling and Simulation
Enterprise, SoS	SD
System	SD, ED
Sub System	MC, HR
Component	MC, HR

As the name implies, Monte Carlo simulation or methods are named for the city in Monaco because of the simple random number generator known as a roulette wheel. Monte Carlo methods matured during World War II based upon research into the atomic bomb. Monte Carlo methods provide approximate solutions in the form of a statistical distribution to estimate the behavior of a system by sampling probabilistic input variables.

Event driven simulation are dynamic systems that evolve in time by the occurrence of events at possibly irregular time intervals. By capturing the process and sampling the probabilistic input variables, we can develop a statistical distribution of the behavior of the system.

Advantages and Disadvantages of Simulations

The advantages of simulation are:

1) Once the model is explained, most people can understand it and accept its results as legitimate representations of the system under consideration (a simulation is more "intuitive"),
2) Simulation can be used for complex, real-world situations or conditions that are not included in analytical models,
3) We can simulate extended periods of time in a short period of time on a computer,
4) It is much less expensive to build something in a computer language and experiment with the model than it is to construct the physical system for experimentation,
5) Simulation allows for easier "what-if" analysis and variations on the existing model (sensitivity analysis),
6) Relatively straight forward; minimum cost,
7) Easier to apply than analytical methods,
8) Greater flexibility in representing the real system - fewer simplifying assumptions,
9) Precludes loss of people lives & damage to the environment, and
10) Model can be used repeatedly.

The disadvantages of simulation are

1) Is not an optimizer,
2) Does not lead to fundamental understanding (we observe outcomes on a process, but may not understand why the outcomes are as they are),
3) An abused analytical tool that is often used in lieu of physical models,
4) The best simulation languages (most complex) and models can be expensive and require a great investment in time to learn the simulation program,
5) Simulation models do not provide optimal solutions.
6) Only the conditions that are included in the model can be examined, and
7) You may not discover fundamental relationships that are sometimes illuminated by analytical models.

Summary

Modeling and simulation (M&S) continue to be key elements of SE throughout the acquisition life cycle especially early in programs. M&S allow program managers to quickly develop Concepts of Operations (CONOPS). Further along in the life cycle M&S can used for detailed design. M&S can be used in a distributed collaborative environment that supports authoritative information exchange and rapid refinement of the design or concept, and over the system life cycle to respond to changing circumstances such as technological advances, changing threats, tactics, or doctrine. During the early phases of defining the needed M&S environment, the systems engineering team must also establish the metrics to be used for evaluating candidate concepts. The specifics of the M&S environment can then be filled in such that meaningful measures of merit can be extracted from the simulations and used to focus further rounds of simulation, critical experiments, and human-in-the-loop testing.[13]

For the systems engineer or engineering manger, M&S should be applied throughout a system's life cycle in support of systems engineering activities. Systems engineers integrate the use of modeling and simulation tools and technology into all development/ management activities, as well as, plan for life-cycle application, support, and reuse of models and simulations. Since M&S plays such a big role in test and evaluation, system engineering planning must be especially clear in integrating testing and M&S activities.

[13]Excerpted from DoD 5000.1.

Discussion Questions and Problems

DQ 1.1 – What was your preconceived definition of modeling and simulation before your started this class?

DQ 1.2 – Can you think of problems that cannot be modeled using a simulation (hint: a simulation only gives you an answer for what you have modeled)?

DQ 1.3 – Simulations are essential models for processes with a mathematical representation of the entity behavior. Which is more difficult to model: the process or the entity behavior?