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Modeling and Simulation in system life cycle

M.J. Simões-Marques*

CINAV-Portuguese Navy, Alfeite, 2810-001 ALMADA, Portugal

Abstract

M&S plays a key role in ensuring the success of innovative systems, which meet existing needs or introduce new standards, by disrupting the *status quo*. In last decades the technological evolution offered the opportunity to broaden the fields of application of digital equipment, making them ubiquitous. Giving examples of this is almost pointless, since everyone observes the evolution of the "classic" products into new products, which very often result from the hybridization of different devices. Cell phones are an obvious example. Nowadays besides voice communication services, they offer other forms of communicating as well as a myriad of other features. However, innovations have some risk of failure associated to them, for many different reasons. Acceptability of a product depends on a host of attributes which include cost, reliability, and usefulness. This work will address how M&S can be used to improve the support to the decision processes to define why systems are needed, what the best implementation alternatives are, and how to develop, operate and sustain them in an effective and efficient way. The discussion will focus the domain of defense systems, considering the characteristics and requirements of the different life cycle stages.

Keywords: M&S; Defense; System of systems; Life cycle

1. Introduction

Modeling and Simulation (M&S) can assume a substantial number of forms and be used in a multitude of problem areas in many disciplines. The evolution and growing dimensions of this discipline are very well captured and described, for instance, in [1, 2, 3]. Independent of the field of application, which is quite broad, M&S are man-made representations of a system. 'Modeling' addresses the static representation of the system entities, while 'Simulation' addresses their behavior or dynamic over time. M&S plays an important role in ensuring the success

* Corresponding author. Tel.: +351 - 91 21 71 753.
E-mail address: mj.simoes.marques@gmail.com

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of innovative systems, which meet existing needs or introduce new standards, by disrupting the status quo. For instance, in last decades the technological evolution (e.g., computing power, miniaturization, autonomy, new materials, and reduced costs) offered the opportunity to broaden the fields of application of digital equipment, making them ubiquitous. This evolution is having also a significant impact in the way humans used to interact with conventional equipment.

Giving examples of this is almost pointless, since everyone observes the evolution of the "classic" products into new products, which very often result from the hybridization of different devices. Cell phones are an obvious example. On the early days they were mobile phones. Nowadays besides voice communication services, they offer other forms of communicating (e.g., text, video), as well as a myriad of other features such as access to internet, office applications, entertainment applications, camera. The interaction evolved from the conventional keyboard (multi-tap) to (multi-)touch-screen interfaces and to voice and gesture controlled devices. On the other hand, since mobile phones are interoperable with other devices, locally or remotely, one can make calls using the hands-free functionality provided by vehicular multimedia and navigation systems; or one can monitor and control devices at home (e.g., home security system, digital cable box, household appliances). These types of evolutions are also changing the way of doing business both in civil society and in security and defense organizations.

However, innovation has some risk of failure associated to it, for many different reasons. Acceptability of a product or system depends on a host of attributes which include cost, reliability, and usefulness. M&S is helpful in addressing most of these attributes. This work will address the role of M&S in the system life cycle, taking as example defense systems. For this it will be discussed how different forms of modeling can be used, for instance, on the conceptual phase of a new system or on the improvement stages of a system to establish the design alternative that better suits its context of use. It will also be discussed different simulation approaches which can be used, for instance, to experiment and evaluate the functionalities and behavior of a system, as well as the forms interaction with users. Furthermore, the paper will discuss how M&S can be used in other phases of a system life-cycle to support its production, service and retirement.

2. Key concepts

2.1. System life cycle

Considering the complexity and interdependency of most systems we rely on, life cycle management is critical to ensure an integrated approach and the adoption of consistent processes. This is true for civil society, in general, and is particularly true for national Armed Forces and for international defense organizations, such as the North Atlantic Treaty Organization (NATO), which need to develop capabilities, often through cooperative programs. Developing such capabilities implies a strict adherence to principles of cooperation and interoperability, efficiency, collaboration with Industry, and quality, which requires commitment to system life cycle management (SLCM). Defining system life cycle stages and processes is a key factor for SLCM. This is the goal of ISO/IEC/IEEE 15288:2008 [4], which establishes a common framework for describing the life cycle of systems created by humans, and defines a set of processes and associated terminology. These processes can be applied at any level in the hierarchy of a man-made system's structure for a great variety of business domains (e.g., aerospace, telecommunications, military systems, ship building, IT), involving combinations of hardware, software, data, humans, processes, procedures, facilities, materials and naturally occurring entities. NATO SLCM policy [5], which is based on this civil standard, provides guidance on the implementation of SLCM, aiming to mitigate risk, reduce acquisition times and to identify, quantify and control life cycle cost. Further guidance, as well as terms and definitions for NATO programmes, is provided in other NATO publications and handbooks, such as [6] which sets a framework for establishing cooperative, joint, multinational, and commonly funded programmes. When compared with ISO standard, [6] introduces an extra stage that precedes all the others in the system life cycle, designated "pre-concept" to describe the actions required to trigger the system life cycle. Table 1 lists and characterizes the stages of a system life cycle based on [6], which closely follows the ones set by [4]. Considering a classic "why-what-how" perspective for the development of a defense capability or a system, the "why" question is covered during the first stage (pre-concept), the "what" question regards the second stage (concept), and the "how" question is answered mainly during the subsequent two stages (development and production) [7]. It is also possible to analyze the system life cycle considering the core research, development and engineering (RD&E) activities developed at each stage. The “pre-concept” and “concept” stages are focused in Science & Technology Development and the main activities relate with “discovery” (basic research, and research & engineering) and “innovation” (materiel solution analysis); during the “development” and “production” stages the focus is on Program Engineering & Acquisition and the main activities are “advanced development” (Technology Development) and “engineering & production” (Engineering & Manufacturing Development, and Production & Deployment); and, finally, during the “service” stage the main activity is “support” (Operations & Support, Sustainment) [8].

Table 1. Stages of the life cycle (adapted from [6, 7, 8]).

Stage	Description	Why-What-How	RD&E
Pre-concept	• identify and document stakeholder requirements; • identify areas of risk to the capability delivery.	Why	Discovery
Concept	• refine and broaden the studies, experiments, and engineering models pursued during the Pre-Concept Stage; • develop preliminary system requirements and a feasible design solution	What	Innovation
Development	• develop a system that meets or exceeds the stated requirements and can be produced, tested, evaluated, operated, supported and retired	How	Advanced development
Production	• manufacture and test the system, and produce related support and enabling systems as needed	How	Engineering & Production
Service	• operate the product at the intended operational sites, including modification and upgrades; • deliver the required services with continued operational and cost effectiveness.	-	Sustainment
Support (part of Service)	• provide logistics, maintenance, and support services that enable continued operation and sustainable service.	-	Support
Retirement	• demilitarize and dispose of the system at the end of its useful life and remove related operational and support services.	-	-

Identical perspective is given by the system engineering view of the processes envolved in the system life cycle, represented in the V-model (Fig.1). The left side of the V relate with the decomposition of the needs and requirements to define the an adequate solution (build the right system); while the right side of the V relate with the integration of the solution and the verification that it complies with the requirements (build the system right) [9].

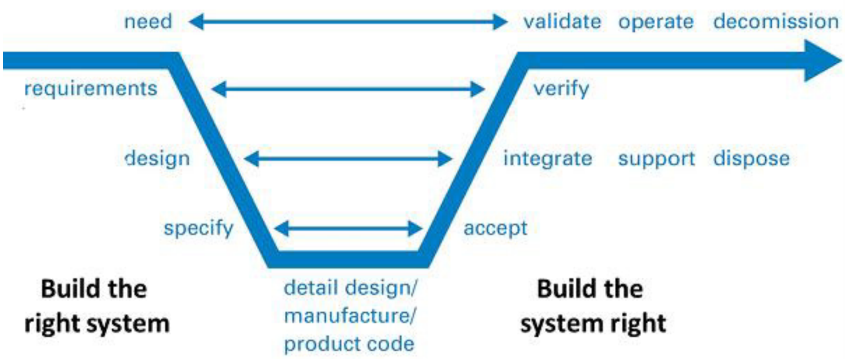

Fig. 1. System Engineering life cycle V-model (adapted from [9]).

Quite often, the 'systems' we consider are integrated by sub-systems and/or are part of a larger system. This enphasizes the growing role of system of systems (SoS) as an approach to build complex solutions. This is particularly true in the defense capabilities[1] edification process. From the system engineering perspective, a SoS corresponds to a multi V-model, therefore in this context all the stages of the life cycle are more challenging. In fact, very seldom a SoS is developed from the very beginning to fulfill a specific purpose. Usually the constituent systems have independent ownership, life stages, and development and sustainment models.

As noted in [10], because of the characteristics of SoS system engineering, M&S can be a particularly valuable tool to help on the activities of the different stages of the life cycle, since it can support: (i) analysis of architecture approaches and alternatives; (ii) analysis of requirements and solution options; (iii) test and evaluation at different stages throughout the process; and (iv) understand the end-to-end performance of the overall SoS prior to implementation.

In fact, besides the support to system engineering-focused activities, M&S can play many other roles during system life cycle providing support from basic research to retirement, including prototyping, planning, and training, just to give some examples.

Despite its particular relevance in the SoS context, the role of M&S holds true in the life cycle of any individual system. In the next subsection some key concepts regarding M&S will be presented.

2.2. Modeling and Simulation

The designation M&S refers to the development and/or use of models and simulations. M&S can be used with the purpose of performing experiments (e.g., decision support, understanding, and education), of providing experience under controlled conditions (e.g., training and entertainment), and of imitation [11].

The term 'Modeling' refers the static and validated representation of a system, entity, phenomenon, or process. This is done using physical, mathematical, or otherwise logical representations (i.e., 'models').

The term 'Simulation' addresses the behavior or dynamic of models over time. Simulations can assume many forms and employ or not software and hardware. On one extreme of the spectrum are 'live simulations' where actual players use genuine systems in a real environment (for instance, firefighting drills); in this case the situation is 'fake' but the players use real equipment and procedures in a controlled environment, without any synthetic (e.g., digital) elements in the scenario. On the other extreme are 'constructive simulations' where simulated players use simulated systems in a synthetic environment; i.e., every element (player-system-environment) is a representation of reality. An intermediate type is 'virtual simulations' where actual players use simulated systems in a synthetic environment. It is possible to perform complex simulations (designated 'live-virtual-constructive' or 'LVC' simulations) that combine the three types.

As Ören notes, regardless of whether or not the simulation is computerized and whether it is carried out on pure software or on any type of hardware/software M&S can be used to [11]:

- Support Decision-Making – for prediction (of behavior and/or performance), evaluation of alternatives, sensitivity analysis, evaluation (of behavior and/or performance) of engineering design, virtual prototyping, testing, planning, acquisition, and proof of concept;
- Understanding – for the analysis of problems, since several models can be tested until the behaviors of the model and the real system match under the same or very similar conditions;
- Education – for teaching any type of dynamic system;
- Training – for gaining/enhancing competence through experience under controlled conditions (virtual simulations to enhance motor skills to gain proficiency of use of equipment such as an airplane, a tank, or a car; constructive simulations (e.g., war gaming, international relations gaming, business gaming) to enhance decision making and/or communication skills; and live simulation to gain/enhance operational skills in a controlled environment).

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[1] The military capability components include doctrine, organization, training, materiel, leadership, personnel, and facilities (DOTMLPF)

Table 2 presents definitions of some key concepts that are useful to understand and discuss the relationship of M&S and system life cycle as discussed below.

Table 2. Key concepts for discussing the relationship between M&S and system life cycle.

Concept	Definition	Source
Constructive simulation	Simulated players use simulated systems in a synthetic environment	[12]
Digital simulation	Simulation or simulators that represent functioning using programming (software) code in a manner that mimics real-world equipment, events, processes, etc	[12]
Hardware-in-the-loop simulation	Simulation and simulators that employ one or more pieces of operational equipment (to include computer hardware) within the simulation/simulator system	[12]
Human-in-the-loop (HITL) simulation	Simulation and simulators that employ one or more human operators in direct control of the simulation/simulator or in some key support function (e.g., decision making)	[12]
Life cycle	The evolution of a system, product, service, project or other human-made entity from conception through retirement	[4, 5]
Live simulation	Actual players use genuine systems in a real environment	[12]
Model	A physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process	[13]
Modeling	Application of a standard, rigorous, structured methodology to create and validate a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process	[13]
Modeling and Simulation (M&S)	The use of models, including emulators, prototypes, simulators, and stimulators, either statically or over time, to develop data as a basis for making managerial or technical decisions.	[13]
Modeling and Simulation (M&S)	The discipline that comprises the development and/or use of models and simulations	[14]
Simulation	A method for implementing a model over time	[13]
Software-in-the-loop simulation	Simulation and simulators that employ one or more elements of operational software (computer programming code) within the simulation/simulator system	[12]
System	A combination of interacting elements organized to achieve one or more stated purposes	[4]
Synthetic environment (SE)	A computer based representation of the real world, usually a current or future battlespace, within which any combination of "players" may interact. The players could be computer simulations, people or instrumented real equipment. SEs are usually taken to include a set of networked and interoperating simulations.	[15]
System of Systems (SoS)	A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities	[16]
Virtual simulation	Actual players use simulated systems in a synthetic environment	[12]

3. The role of M&S in system life cycle

The current section will present how different types of M&S can be used to support the activities at each stage of a system life cycle. To simplify the text the generic term 'system' will be used; however, this term is meant to be understood in a broad sense, meaning that the basic discussion encompasses from complex SoS to more modest systems. Naturally the selection of an adequate M&S type, and the effort and resources required depend on the specifics of a particular case.

3.1. Pre-concept stage

As presented in Table 1, the main purpose of this stage is to identify and document stakeholder requirements, and to identify areas of risk to the capability delivery [6]; answering the question "why" to develop a capability [7]. The inherent activities relate with "discovery" [8] and provide focus for research and industry to ensure delivery of a system to an acceptable timescale and affordable cost [6].

The use of M&S in this stage on the one hand is related with the processes of research and development, particularly the ones related with science, engineering and emergent technologies, which are one of the natural fields of application of this discipline. On the other hand, M&S can be used to support the decision-making process regarding the management of capability needs. In this case M&S can be used, for instance, to develop models to predict the effects of new or modified capabilities, evaluate alternatives, perform sensitivity analysis, experiment with virtual prototyping, or make proofs of concept.

3.2. Concept stage

As mentioned before, the main purpose of this stage is to refine and broaden the studies, experiments, and models pursued during the pre-concept stage; and to develop preliminary system requirements and a feasible design solution [6]. In this stage any type of M&S used to support defense experimentation is particularly useful. "Defense experimentation" is the application of the experimental method to the solution of complex defense capability development problems, potentially across the full spectrum of conflict types (e.g., warfighting, peace-enforcement, humanitarian relief and peace-keeping operations) [15].

According to [15] an "experiment" is an empirical means of establishing cause-and-effect relationships through the manipulation of independent variables and measurement of dependent variables in a controlled environment. The same source refers that "experimentation" is enacted by the testing of hypotheses, which can be based on M&S, namely, analytic wargames, constructive, virtual, live and HITL simulations, eventually using synthetic environments. For instance, analytic wargames typically employ command and staff officers to plan and execute a military operation, often with some form of constructive simulation adjudicating outcomes between turns (sometimes overnight) [15].

Another useful approach described by [15] is "model-exercise-model," which is a process that iteratively combines modeling (usually constructive simulation) and empirical techniques of analysis. This approach normally comprises three phases: (i) the initial use of a constructive simulation helps understanding key drivers and sensitivities; (ii) the realization of an empirical event ("exercise") whose conditions replicate one or more of the modeled conditions; and (iii) a new modeling phase, considering validated, calibrated and/or modified empirical data from the previous phase; the results of the final models are used to perform extrapolations from the empirical test condition.

3.3. Development stage

Considering that the main purpose of this stage is to develop a system that meets or exceeds the stated requirements and can be produced, tested, evaluated, operated, supported and retired [6], any M&S means that support this purpose are helpful. In this particular stage M&S can be used for the prediction of behavior and performance of systems, the evaluation of alternatives, the conduction of sensitivity analysis, the evaluation of designs, or the creation of virtual prototyping [11]. Naturally one key dimension of systems' design is human factors and ergonomics, therefore the M&S tools for HF&E are particularly relevant in this stage (e.g., 3D Human-CAD, virtual prototyping, human performance models, biomechanical models, cognitive models, risk assessment models, human fatigue models, usability testing, eye-tracking). It can also be used to support testing, to optimize planning and acquisitions, to perform proof of concept, and also for SoS interoperability integration [11, 14].

3.4. Production stage

As presented in Table 1, the main purpose of this stage is to manufacture and test the system, and produce related support and enabling systems as needed [6]. There is host of literature addressing the use of M&S in engineering, in general, and in industrial engineering, in particular. The M&S application range is very wide, encompassing decision support, planning, scheduling, production optimization, supply chain optimization, testing, and cost estimation, to refer some.

3.5. Service stage

The purpose of this stage is to operate the product at the intended operational sites, including modification and upgrades, and to deliver the required services with continued operational and cost effectiveness. This stage ends when the system is taken out of service [6]. At this stage one of the key activities is training, which is the process of teaching, familiarizing and bringing to a known and common skill level operators or users of a system [15]. Depending on the purpose training can be categorized as individual, team or collective training.

A common purpose of M&S in training is to deliver a representation of a system allowing the gain of experience to enhance one of the three types of skills: motor skills (using simulators), decision making and communication skills (using virtual simulations and serious games[2]), and operational skills (using live simulations) [11].

A fairly obvious example of the use of M&S in training is the use of flight simulators (a virtual simulation in a synthetic environment) to develop the skills of pilots. This is an example of a HITL simulation in which the human performance is improved, tested and assessed using a simulator of manned equipment.

Note that, contrary to what happened in the previous stages where M&S was used to predict and assess systems performance, in the case of training M&S is used to predict and assess human performance.

A different dimension of this stage of the life cycle is the system evolution, through modifications and upgrades. The activities required for this purpose are identical to the ones of the previous stages; therefore all the M&S applications discussed before can be useful again.

3.6. Support stage

As presented in Table 1, the main purpose of this stage is to provide logistics, maintenance, and support services that enable continued operation and sustainable service. The Support Stage is completed with the retirement of the system and termination of support services [6].

M&S can be used, for instance, for training purposes (e.g., system engineering decision-making training, troubleshooting training), for planning, scheduling and optimization of logistic operations or for upgrade impact simulation.

3.7. Retirement stage

The main purpose of this stage is to demilitarize and dispose of the system at the end of its useful life and remove related operational and support services, ensuring that disposal is carried out in accordance with legal and regulatory requirements regarding safety, security and environment [6].

The use of M&S can address, for instance, the effects of suppressing a capability, through capability impact simulations; can support the analysis of material disposal to environment and safety, using impact simulations; or can be used in live simulations to support training (e.g., the retired system serves as target) or technological research (e.g., the disposal of the system is monitored to collect data) [17].

4. Conclusions

The paper introduced some basic concepts related with system life cycle and with M&S, and discussed different roles that M&S can play throughout the life cycle of the systems. It was noted that, despite the type of M&S used may vary depending on the life cycle stage and on the specific objectives pursued, the main goals of using this invaluable resource are to understand what the best alternatives are and to support the needs and responsibilities of systems stakeholders (e.g., decision-makers, researchers, developers, users, maintainers).

The discussion addressed the importance of M&S from the very beginning of the system life cycle, to support decision makers regarding the analysis of the reasons for the edification of new capabilities, and identified different

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[2] "Serious games" is a designation used to refer games that are not used for entertainment purposes used, for instance, defense, education, health care, emergency management and politics.

ways for M&S to support the selection of adequate development and implementation alternatives. Therefore, M&S helps on the identification of adequate solutions (i.e., build the right system) and also on the validation of the compliance of the produced systems with respect to the established requirements (e.g., build the system right). It was also discussed how M&S can contribute to the enhancement of required skills among systems system operators and maintainers.

Although all types of simulation can be used in the different stages of a system life cycle, it is natural to have an higher prevalence of constructive simulations at the concept stage, and to observe a gradual transition to virtual simulations in the development and production stages, followed by an increase in the proportion of live simulations as systems enter the service stage.

It was noted also that M&S can be used to support the evaluation of systems performance (mainly using constructive simulations) as well as human performance (mainly using HITL and live simulations).

As a conclusion, M&S offers a broad variety of means which can be used, during the different stages of the life cycle of systems, to improve the support to the decision making processes to define why systems are needed, what the best implementation alternatives are, and how to develop, operate and sustain them in an effective and efficient way.

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