

# THE QUEST FOR THE MODELLING AND SIMULATION BODY OF KNOWLEDGE<sup>1</sup>

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## Abstract

The purpose of this paper is to explore the body of knowledge associated with the modelling and simulation activity. The fact that modelling and simulation is emerging as a recognized professional discipline suggests the urgent need for a generally accepted consensus of the scope of knowledge that should reasonably be expected from its practitioners. We take a pragmatic approach to formulating a proposal for this body of knowledge that begins with the recognition of its essential inter-disciplinary nature. The main thrust of the development evolves from an examination of the tasks that are typically carried out by a modelling and simulation practitioner and from an informal view of the lifecycle of a typical modelling and simulation project. The extent of the knowledge landscape that emerges is substantial and is likely more than can be reasonably be expected from any individual. Area specializations therefore become a natural consequence and possible alternatives are suggested.

## Introduction

For more than five decades, the supporting role of modelling and simulation (M&S) has been continuously expanding in system design, analysis and optimization and, as well, in education and training. This growth can be seen not only in the range of application areas but also in the nature of the problems that are being addressed. The growing importance and scope of M&S has given rise to the requirement for both specialized knowledge and specialized competence in those who assume leadership roles in M&S projects.

A number of indicators suggesting the emergence of modeling and simulation as an identifiable professional discipline have become clearly apparent in recent years. These include the development various academic programs (e.g.; those at California State University at Chico, Old Dominion University and the University of Central Florida) as well the recent proposal of a code of ethics for the profession [Ören et al, (2002), Ören (2002)]. There is, as well, the initiation of the Modeling and Simulation Professional Certification program under the auspices of the National Training Systems Association (see: [www.simprofessional.org](http://www.simprofessional.org)). The fact that there is highly specialized knowledge associated with the M&S activity is amply reflected in the growth of an M&S service industry that supports the needs of the M&S enterprise within specific domains/industries.

In spite of these very significant and encouraging developments, there continues to be no generally accepted agreement on what exactly constitutes the body of knowledge which the M&S domain embraces. Likewise there is no particular agreement on the knowledge and skills that should be expected from an individual who claims the status of an M&S professional. These circumstances can have a serious restraining impact on the continued vigor in the development of the profession. An investigation of these issues is the main purpose of this paper.

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## The M&S Discipline

Any exploration of the nature of the M&S body of knowledge (BoK) must necessarily emerge from a coherent and widely accepted perspective of what the M&S discipline actually is. Or, alternately, from a perspective of what an M&S professional actually does. A comprehensive development of this prerequisite would, in itself, be an undertaking of substantial challenge and is certainly beyond the scope of this presentation. We provide instead several key features of the discipline to serve as a foundation for the perspective we propose for the M&S body of knowledge.

It must, first of all, be recognized that M&S really is two distinct, but interdependent, notions; namely, *modelling* and *simulation*. As might be expected, each of these contributes significantly to the BoK we seek to develop. A second fundamental feature is the inherent interdisciplinary nature of M&S. This is not to suggest that there are not aspects of M&S that are genuinely distinctive to it; e.g., the techniques for managing time advance, the special requirements of validation, the challenges introduced by distributed/parallel computing environments, the protocols for ensuring the interoperability of simulation models. But the BoK necessarily has its primary origins in the sister disciplines from which M&S has drawn its technology and most of its methodological basis. This is explored further in the subsequent discussion.

We choose the following as our working definition of simulation:

*Simulation is goal-directed experimentation with dynamic models*

Although not explicitly stated, there is in the above an implicit understanding that the experimentation is being carried out in a computer context. The notion of “model” similarly implies a representation that is embodied within a computer program. The steps required to achieve this particular (and essential) embodiment of the model, are a core aspect of the M&S activity. It should be observed that the alternative of experimentation with physical models remains an important data/insight generating activity; however, this category of “simulation” is outside the scope of the considerations in this paper.

What does an M&S practitioner do? An examination of this issue can provide a valuable window into the BoK we seek to characterize. A list of activities which is, by no means exhaustive, would include the following:

- (a) assimilates application-domain specific knowledge
- (b) provides problem analysis support in collaboration with the end-user in order to assist with a clear formulation of the requirements specification
- (c) ensures proper and comprehensive documentation of the assumptions inherent in the underlying dynamic model together with its data requirements its intended scope of relevance.
- (d) transforms relevant aspects of the requirements specifications into a representation that can serve as a vehicle both for confirming the dynamic model under consideration and for communicating the model to program developers
- (e) assists in the development of the computer program for the simulation model (typically using some special purpose simulation language)
- (f) formulates and carries out appropriate verification and validation tests to establish the credibility of the simulation model
- (g) when relevant, assists with ensuring compliance with protocols for implementing the simulation model within a distributed computing environment and/or with ensuring inter-operability with other models
- (h) assists with the design of the simulation experiments that will achieve the goal(s) of the study
- (i) ensures that the results from the experiments are correctly interpreted, taking into account limitations of the numerical tools being used and the stochastic features of the model
- (j) assists with the development of specialized end-user interfaces to simulation output (animation, GUI's)
- (k) provides support in the development of data bases for input data (e.g., terrain data) as well as databases for accumulating simulation generated data

This tentative list serves to reflect the breadth of the activities that are associated with the M&S discipline and these must be represented in some suitable fashion in the associated BoK. We note also that similar perspectives on this fundamental question have been presented; e.g., Ören (2000).

It needs to be stressed that no body of knowledge is static, but rather is in a constant state of evolution. The list above is biased to focus on M&S activities that impact the current BoK. There are many important areas of M&S activity that have been omitted from the above list because of this restricted focus; such activities may instead have an impact on the evolution of the BoK. Such activities include: (i) contributes to the advancement of the technology, methodology and/or theory that underlies M&S (typically within a research/development environment); (ii) advances the profession through pedagogical contributions (typically within an academic/training environment); (iii) maintains, manages or markets M&S products or services (typically within a commercial environment).

## **Exploring the M&S Knowledge Landscape**

In this section we begin the construction of key elements of the M&S BoK. These flow from the perspectives discussed above. We begin by noting that every simulation project has a life-cycle, a sequence of stages each with a beginning and an end. It is not our intent to review this life-cycle (a comprehensive presentation can be found in [Balci (1998)]) but we make explicit reference to it since it provides an excellent orientation for the development of the BoK.

The first stage of the life-cycle corresponds to some form of requirements specification. A key aspect of this activity is the development of the dynamic model that underlies the simulation study. Modeling knowledge to support this task is, for the most part, very domain specific. However an excellent foundation for dynamic model building can be obtained through a familiarity with areas such as dynamics, thermodynamics and electric circuits. We refer to the sister discipline that encompasses these as the “Physical Sciences”. Many system models of contemporary interest incorporate queues, hence knowledge of queuing theory (from Statistics) needs to be added here. Generally, dynamic models emerge in the form of mathematical equations, hence a working familiarity with topics from Mathematics such as linear algebra, boolean algebra, and ordinary and partial differential equations is an essential component of the modelling tool-kit. The growing importance of simulation within training environments, suggests that knowledge of learning theories, assessment and training analysis from the field of Education is highly relevant. Likewise knowledge of cognitive modelling, social modelling and human behavior evaluation from Psychology needs to be included in the context of training applications and virtual environments and, as well, in support of the growing importance of simulation models which directly incorporate humans (human-in-the-loop simulations).

Initial domain specific models often evolve into more abstract representations that, in particular, serve to facilitate communication among project team members who generally are not domain experts. Typical vehicles for such “conceptual modelling” are finite state machines, Petri nets, bond graphs, DEVS and rule-based specification. Such conceptual modelling tools have their origins in a variety of disciplines but some; e.g., bond graphs and DEVS, can be considered uniquely an integral part of M&S. In effect, we suggest here that M&S does not rely entirely on knowledge borrowed from other disciplines but has matured to a point where it utilizes its own distinctively unique knowledge. We place many of the tools of conceptual modelling into this category. Several other constituents of the discipline are identified in the subsequent discussion.

Another key phase in the lifecycle of a simulation project is the development of the simulation program. This has two main aspects. The first is the development of the simulation model itself; namely, the program code whose execution provides the dynamic behavior (in some desired format) of the system under study. The simulation model can be viewed as the product of a transformation of the conceptual model into the format of an executable computer program. Such code is, by and large, written using specialized simulation languages but nevertheless knowledge of program design techniques typically associated with software engineering, is necessary. Furthermore, there are often many important decisions requiring significant technical insight which need to be made. For example, if the model involves the solution of differential equations, the knowledge of many topics from numerical mathematics is needed e.g., solution methods, step-size selection, error control mechanisms etc. If the model incorporates stochastic elements, then knowledge of a whole range of topics from statistics becomes mandatory in developing the simulation model; e.g., random number generation, probability distributions, variance reduction, design of experiments, etc.

The program code for the simulation model does not execute in isolation. It is normally embedded within a larger program context which provides the accessory elements of the overall simulation program. This auxiliary program code is, in many respects, no less important than the embedded simulation model because it provides the features (often substantial) that are appear in the requirements specification. The potential scope of these features is exceedingly broad. For example, if there is an optimization aspect to the problem, then optimization processes must be introduced and appropriate knowledge from say, industrial engineering is needed. Alternately, there may be significant output data storage and/or display requirements which, respectively, require knowledge of database and computer graphics/animation techniques from computer science. Projects which have a training orientation or a focus on the entertainment domain will likely require the insights of several areas of psychology; e.g., human perception and behavior analysis. The ever-expanding size/complexity of simulation models has given rise to greater demands on computing power which often is best achieved by distributing the computational load over multiple processors. This introduces the need for knowledge of distributed and parallel computing techniques from computer science. In a similar context, there is a growing need to interconnect in a seamless manner multiple distinct models which execute on machines which are physically separated by large distances. This introduces the need for knowledge of computer networks (from computer science) and the protocols that are emerging for inter-operability of simulation models.

It must be stressed that the development of a simulation program is no different than the development of any software system. Hence knowledge of all key aspects of software engineering is necessary in the program development phase of a simulation project. Included here are topics such as project management, documentation, modular program design, quality assurance techniques, testing etc. Perhaps above all, are the notions of verification and validation. Validation is especially challenging in as much as there exists the underlying notion of a simulation model whose credibility (within the framework of the goals of the study) must be convincingly established.

The final phase of the life-cycle focuses on the results generated by the simulation program. These need to be evaluated in terms of the initially formulated goals of the study (as embedded in the requirements specification). Often a high degree of domain knowledge is needed here but there are contributions that can be reasonably expected from an M&S professional. These could include assistance with data analysis (in the case of stochastic systems), sensitivity analysis, project documentation, presentation of results and assessment of training efficacy (in training environments)

The constituents of the BoK as identified in the discussion above are summarized in Table 1 (first two columns). The format of the presentation in this Table emphasizes the essential inter-disciplinary nature of the M&S activity.

## **Specializations**

The scope of the M&S body of knowledge proposed in Table 1 is, realistically, beyond the embrace of most individuals. It is therefore reasonable to suggest the existence of specializations within the M&S profession where each of these is associated with a proper subset of the global BoK.

Identification of meaningful specializations that will be generally accepted by the M&S community will likely be a difficult task because of the need to accommodate a large range of exiting expertise and a large range of marketplace requirements. Dealing with the topic comprehensively will require insightful exploration and is certainly beyond the scope of the current discussion.

Nevertheless there is one straightforward approach to handling the problem that has a rational basis and is, at least, illustrative of the possibilities. In this approach we simply extrapolate from the major stages associated with the life-cycle of a simulation project. A possible outcome of such an approach is the identification of three specializations which we designate as Model Developer, Simulation Program Developer and End-User Support. Knowledge areas required by each of these can now be easily indicated in the appropriate columns of Table 1. A refinement here is also possible; namely, a necessary level of knowledge in each of the topics can be designated; e.g., H=high, M=medium, L=low while a blank implies that absence of knowledge is not significant. The collection of topic areas with an H or M entry could then be considered as the body of knowledge for the specialization.

Primarily in the interests of illustration, we have implemented this process and provided in Table 1 tentative entries for the three identified specializations.

## Conclusions

Although there are many significant indicators to suggest that the activity of modeling and simulation has matured to the level of a professional discipline, there continues to be a disturbing absence of a coherent and widely accepted statement of the body of knowledge that characterizes the discipline. By examining some fundamental features of the M&S activity such as the M&S life-cycle and the array of tasks typically carried out by M&S practitioners, we have formulated a characterization of the M&S BoK. The presentation explicitly recognizes the inherently inter-disciplinary nature of the discipline. The format of the presentation allows for simple adaptation to accommodate both the variations resulting from modified perspectives and, as well, the inevitable changes necessitated by the rapid evolution of the discipline.

The broad scope of the proposed BoK implies that it is beyond the embrace of most individuals. This suggests that there is a need to identify a collection of specializations within the M&S profession, each characterized by its own “local” BoK. This is a topic which needs to be explored in depth. Nevertheless a tentative initial proposal has been presented.

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<b>DISCIPLINE</b>	<b>TOPIC</b>	<b>Model Developer</b>	<b>Simulation Program Developer</b>	<b>End-User Support</b>
<b>Computer Science</b>				
	programming languages	L	H	M
	data structures		H	
	computer architecture/organization		H	L
	file management		H	
	database systems	L	H	L
	operating systems		H	
	computer networks		H	
	computer graphics		H	
	parallel computing		H	
	distributed systems		H	
	artificial intelligence(*)	M	H	
<b>Education</b>				
	learning theories	M		
	assessment			M
	training analysis			M
<b>Industrial Engineering</b>				
	operations research		M	
	linear programming		H	
	dynamic programming		H	
	nonlinear optimization		H	
	sensitivity analysis		L	H
	cost models		L	
	human factors	L		L
	organizational behavior	L		L
<b>Mathematics</b>				
	numerical analysis		H	
	boolean algebra	M	L	
	linear algebra	H	M	
	ordinary differential eqn's	H	M	L
	partial differential eqn's	H	M	L
<b>Modeling &amp; Simulation</b>				
	conceptual modeling formalisms(**)	H	M	L
	data visualization(***)		H	
	standards	H	H	H
	distributed simulation	M	H	M
	model repositories	H	H	M
	synthetic/virtual environments	M	H	M
	inter-operability of	M	H	M

	simulation models(****)			
<b>Physical Sciences</b>				
	dynamics	H	L	L
	thermodynamics	H	L	L
	electric circuits	H	L	L
<b>Psychology</b>				
	human perception	L	M	
	cognitive modeling	H		
	neural level modeling	H		
	behavior evaluation		L	H
<b>Software Engineering</b>				
	project management		H	
	documentation	H	H	M
	(modular) program design		H	
	lifecycle models		M	
	verification & validation	M	H	H
	testing	M	H	M
	maintenance		M	H
	quality assurance		H	L
	repositories	M	M	
	metrics		L	
	user interface design		H	
<b>Statistics</b>				
	queuing theory	H		M
	probability distributions	H		M
	random number generation	M	H	
	hypothesis testing		L	H
	variance reduction		H	H
	design of experiments		M	H
	performance measures	M		H
	data analysis		L	H

(\*) >>expert systems, fuzzy systems, genetic algorithms, neural networks, intelligent agents

(\*\*) >>>rule-based specification, Petri nets, bond graphs, DEVS, finite state machines

(\*\*\*) >>>graphics, animation, virtual reality

(\*\*\*\*) >>>DIS, CORBA, HLA

**TABLE 1**

**A Discipline-Oriented Taxonomy of the M&S Body of Knowledge**

