The Importance of a Comprehensive and Integrative View of Modeling and Simulation

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ABSTRACT

A comprehensive and integrative view of modeling and simulation (M&S) is offered. This view may be used to support the efforts of policy makers who would like to promote policies about simulation-based activities. This article is part of the M&S Body of Knowledge development activities sponsored by NTSA.

Keywords: The big picture of modeling and simulation**,** model-based simulation, model-based activities

1. INTRODUCTION

D. Bell who promoted the concepts of post-industrial society" and "information age" also predicted the importance of simulation. In a seminal article, he posited that abstract theories, models, simulations, decision theory, systems analysis will the methodologies in post-industrial societies (Bell 1976). He also expresses that "The key political problems in a post-industrial society are essentially elements of science policy."

After many success stories of modeling and simulation (M&S), possibilities are still growing on what one can achieve by proper use of M&S knowledge. At the dawn of the 21st century, M&S is indeed a critical area for the well-being of many advanced countries. Taking advantage of the full benefit of model-based simulation as well as complementary model-based activities wait (1) to be tapped and (2) offer opportunities for advanced developments in associated theories, methodologies and technologies. In other words, decision makers who can perceive the big picture of M&S will be influential in taking advantage of the opportunities offered by M&S. This article is part of the M&S of Knowledge development activities (Ören 2006a, Waite). Ören's work is sponsored by NTSA

2. SIMULATION

Simulation is used for hundreds of application areas and can be perceived from different perspectives. Having a comprehensive and integrative view of M&S is essential to benefit from its full potential. As seen in Table 1, M&S can be perceived from the following perspectives: Purpose of use, problem to be solved, connectivity of operations, and types of knowledge processing. Final version of the article will include additional perspectives from (Ören, 2005).

Table 1. Perceptions of M&S from Different Perspectives

Perception with respect to	Perceptions of Simulation
Purpose of use	Perform **experiments** for: - Decision support - Understanding - Education Provide **experience** for: - Training - Entertainment Imitation (fake)
Problem to be solved	Black box perception (M&S is an infrastructure to support real-world activities)
Connectivity of operations	Stand-alone simulation Integrated simulation
Types of knowledge processing	Computational activity Systemic activity Model-based activity Knowledge generation activity Knowledge processing activity

2.1 Purpose of use

Table 2 highlights three purposes of use of M&S. As a process, the term simulation has a non-technical and two technical meanings.

Table 2. Three Purposes of Use of M&S

Purpose of use of simulation	Type of simulation
Perform **experiments** for: Decision support Understanding Education	- Simulation
Provide **experience** (under controlled conditions) for: **Training** (gaining / enhancing competence): - motor skills - decision and/or communication skills - operational skills **Entertainment**	 - Virtual simulation - Constructive simulation - Live simulation - Game
Imitation	- Fake

As a technical term, two main types of usages of M&S can be identified. M&S is used: (1) to perform *experiments* (for decision support, understanding, and education) and (2) to provide *experience* (for training and entertainment) through controlled conditions.

The technical meanings cover any type of simulation regardless whether simulation is computerized or not and whether it is carried out on pure software or on any type of hardware/software. Furthermore, both of the technical meanings allow top down decomposition of the entities and activities involved and thus enable their systematic and hierarchical elaborations.

As a non-technical term, the term simulation has been used in English since 1340 and means "imitation" or "fake." In this article, we focus on the technical meanings of the term simulation.

2.1.1 Experiments: In areas other than training and entertainment, simulation is goal-directed *experimentation* with dynamic models. These areas include decision support, understanding, and. education.

"Experimentation is one of the key concepts in scientific thinking since Francis Bacon (1561-1626) who advocated it in 1620 in his Novum Organum. (New Instrument). Bacon's work was a categorical departure from and reaction to "Organon" (the Instrument) which was the title of logical works of Aristotle (384-322 B.C.) which itself had an 'unparalleled influence on the history of Western thought.'" (Ören 2002b).

Hence, the technical definition related with experiments also ties simulation to the origins of modern scientific thinking. However a programmer's view of simulation would be biased to the execution of the simulation program and would hinder this important point. The superiority of performing the experiments on a model rather than on the real system is also well established.

As outlined in Table 3, use of simulation for decision support includes its use for: prediction, evaluation of alternatives, sensitivity analysis, engineering design, virtual prototyping, planning, acquisition, and proof of concept.

Table 3. Types of Use of Simulation for Decision Support

Prediction of behavior or performance of the system of interest interest within the constraints inherent in the simulation model (e.g., granularity)
Evaluation of alternative models, parameters, experimental and/or operating conditions on model behavior or performance
Sensitivity analysis
Engineering design
Virtual prototyping
Planning
Acquisition (or simulation-based acquisition)
Proof of concept

2.1.2 Experience

As outlined in Table 2, in *training,* simulation is used to gain/enhance competence through *experience* under controlled conditions. Three major types of simulations corresponding to three types of training.

(1) *Virtual simulation* (i.e., use of simulators or virtual simulators) is used to enhance *motor skills* to gain proficiency of use of equipment(s) such as an airplane, a tank, or a car. In virtual simulation, real people use virtual equipment in virtual environments; hence the term "virtual simulation."

(2) *Constructive simulation* (or *gaming simulation* such as war-gaming, peace gaming, international relations gaming, business gaming, etc.) is used to enhance *decision making* and/or *communication skills*. In constructive simulation, simulated people use simulated equipment in a virtual environment and real people get experience by interacting with the simulation system.

(3) Live simulation is used to gain/enhance *operational skills* by getting real-life-like experience in a controlled environment. Live simulation is used in diverse areas as military exercises as well as for the training of health specialists. In live simulation, real people use imitation (or virtual or dummy) equipment in the real world.

In *entertainment* (i.e., simulation games, and some types of animation of dynamic systems), simulation provides experience under controlled conditions. "Getting experience under controlled conditions" is the common aspect using M&S for training (i.e., gaining / enhancing competence) as well as for entertainment purposes. The term "serious game" is used to distinguish simulation games used in areas other than entertainment.

2.2. Problem to be solved

With respect to the problem to be solved, a perception of M&S is that it is as an infrastructure to support real-world activities**.** This *is the black box perception* by practitioners, who would like to emphasis that simulation is a tool to achieve other goals. This view allows concentrating to the original problems they face; e.g., for NASA the goal is successful space missions and not simulation; for military, similarly and justifiably, goal is not simulation either. From this perspective, "simulation is perceived as not being the "real thing." This attitude is well documented in STRICOM's motto which is: "All but war is simulation." (Stricom.)

This view leads to successful applications of simulation in familiar areas. However, a broader view of M&S can lead to better appreciation of full scope of possibilities simulation offers. Hence, the limitations of this point of view are: (1) "not even wanting to know what one misses" and (2) to be obliged to have "patches" in the conception of M&S when need arises, instead of benefiting from a comprehensive and integrative view.

2.3. Connectivity of operations

As seen in Table 4, two important categories of simulation can be distinguished with respect to the connectivity of operations of simulation and the system of interest. They are: stand-alone simulation and integrated simulation.

In *stand-alone simulation*, operations of the simulation and the system of interest are independent, i.e., are not connected. Majority of simulations belong to this category.

In *integrated simulation*, operations of the simulation and the system of interest are interwoven. In *integrated simulation*, simulation *enriches* or *supports* real-system operation.

- To *enrich* operations of the real system, the system of interest and the simulation program operate simultaneously to assure on-line diagnosis or augmented reality (enhanced reality) operation.

- To *support* operations of the real system, the system of interest and the simulation program operate *alternately* to provide predictive displays. Predictive displays are based on parallel experiments while the system is running.

Table 4. Types of M&S with Respect to the Connectivity of Operations of Simulation and the System of Interest

Type of connectivity			Type of simulation
Operations of the simulation and the system of interest are:	Not connected		**Stand-alone simulation**
	Interwoven – **Integrated simulation**	To ***enrich*** real system operation	(the system of interest and the simulation program operate ***simultaneously***) - online dignostics (or simulationbased diagnostics) - simulation-based augmented / enhanced reality operation (for training to gain / enhance motor skills and related decision skills)
		To ***support*** of real system	(The system of interest and the simulation program operate ***alternately*** to provide predictive displays) - parallel experiments while system is running

2.4 Types of Knowledge Processing

Simulation can be perceived at different levels of abstraction (Table 1). Simulation is a computational activity, systemic activity, model-based activity, knowledge generation activity, and knowledge processing activity.

2.4.1 M&S as a Computational Activity

The role of the computer spans from generation of model behavior to simulation-based problem solving environments. This point of view is reflected in some definitions of simulation. e.g., "Simulation is the execution over time of models representing the attributes of one or more entities or processes." This *computational* view of execution of simulation program may hinder the high-level possibilities of computer aided problem solving environments such as problem specification, model specification (model synthesis, model composition), experimental frame specification (design and execution of experiments), program generation, and symbolic processing of problem specifications to assure built-in quality. The concept of high level computer assistance in M&S has been promoted since early 1980s (Ören 1982).

2.4.2 M&S as a Systemic Activity

"From a systemic point of view, simulation can be used to find the values of output, input, or state variables of a system; provided that the values of the two other types of variables are known."

As a very important and fundamental contribution to M&S, system sciences provide the basis for modeling formalisms as well as for symbolic processing of models, for a large variety of dynamic systems. These include automata, cellular automata, Lindenmayer systems (or L-systems), Petri nets, System dynamics, bond graphs, goal-directed systems, variable-structure systems, and evolutionary systems. (Ören, Zeigler, Elzas, 1984). Advances of discrete event systems (DEVS) by Zeigler (1984) and many valuable variant theories based on DEVS provide robust theoretic background for the simulation of complex systems modelled as discrete event systems. The first model specification language based on a system theory (Wymore, 1967) for continuous systems described by differential equations was developed in early 1970s (Ören 1971, 1982).

The craftsmanship of a carpenter who can build a beautiful summer cottage cannot scale up to build a skyscrapper which necessitates appropriate engineering knowledge based on theoretical knowledge. Similarly, to build simulation systems for large and complex problems, system theoretic approch is a necessity (if one would like to avoid problems at a later phase of the project).

2.4.3 Simulation as a Model-based Activity

This approach allows construction of simulation-based computer-aided problem solving environments (i.e., advanced simulation environments) (Zeigler et al. 1979; Ören, Zeigler, Elzas, 1984; Elzas, Ören, Zeigler 1986, 1989). Currently, several disciplines adopted model-based paradigms. They include, systems engineering (Wymore 1993), software engineering (mc-swEng), and model-driven enterprise information systems (md-EIS). In M&S, in addition to generation of model behavior, the following can be considered:

- computer-aided modelling (model composability)
- model-base management (or management of model repositories, including their interfaces) (for reusability)
- parameter-base management (for example, in nuclear fuel waste management simulation systems, over a few thousand constants and parameters (some of them to be represented as probability distribution functions) have to be managed.
- symbolic processing of models (See next section on model-based activities).

Of course, in M&S, model-based activities can be best achieved by using an appropriate mathematical system theory.

2.4.4 Simulation as a Knowledge Generation Activity

From an epistemological point of view, simulation is a knowledge generation activity; more specifically, simulation is a goal-directed knowledge generation activity with dynamic models and/or within dynamic environments. This view allows advanced methodologists and technologists to integrate simulation with several other knowledge generation techniques (Ören 1990). At this abstract level, the definition of simulation can be interpreted as follows: "Simulation is model-based experiential knowledge generation." This abstraction facilitates the synergy of simulation with other knowledge generation (and processing) techniques such as: optimization, statistical inferencing, reasoning, and hypothesis processing. In live simulation, simulation as a knowledge generation activity, can easily be integrated with the operations of a real system where real system acts as yet another source for knowledge generation.

2.4.5 M&S as a Knowledge Processing Activity

This view allows advanced methodologists and technologists to integrate simulation with several model-based activities and several other knowledge processing techniques (Ören, 1990) to generate integrated simulation-based problem solving environments. In this case, one can combine modeling, model processing, and other knowledge processing engines to have advanced simulation environments. These include integated use of M&S with optimization, artificial intelligence, software agents. In the last case, agents can also be used for additional purposes to assure quality and reliability of operations.

3. MODEL-BASED ACTIVITIES

As seen in Table 5, in M&S, model-based activities consists of model building, model-base management, and model processing.

Table 5. Types of **Model-based Activities**

1. Model building
- modeling
- model synthesis
- model composition
2. Model-base management
(Management of model repositories)
- model search
- Semantic model search
- model integrity
3. Model processing
- model analysis
- Model characterization
(descriptive model analysis)
- Model evaluation
(evaluative model analysis)
- model transformation
- behavior generation
(generation of behavior of model)

In software engineering, one of the sources of several types of failures has been the practice of maintenance of the code, instead of maintenance of the specification. In M&S, since early days, program generators existed to generate code from specifications. In model-based simulation, model specification can be transformed to a computer code by a program generator. Some of the advantages of model-based simulation are efficiency, reliability, reusability, and interoperability and are summarized in Table 6.

Table 6. Some Advantages of Model-based Simulation

1. Efficiency in Computerization - Model-bases (or model repositories) may contain model specifications that can easily be converted into programs. Hence, programming aspect can and should be fully automated. - This aspect also eliminates programming errors and contributes to the reliability of the computerization of models.
2. Reliability - Models can easily be read and understood by the specialists in the field assuring model reliability - Model specifications can be checked, by specialized software as well as manually for consistency, completeness, and correctness. This aspect is definitely superior to traditional V&V techniques that work on code only and can be the basis for built-in reliability in M&S studies.
3. Reusability and Composability - Model specifications can easily be modified for model reusability as well as model composition. - Some of the model composability techniques can be dynamically applicable for systems that have not only dynamic behavior but also can and should be modified dynamically as the simulation evolves.
4. Interoperability - It is highly desirable to check interoperability of model specifications rather than the codes of models. Executability of code does not necessarily mean its semantic interoperability.

3.1 Model Building

Modeling has been automated since a long time in M&S. The facilities started with filling in questionnaires and use of high level simulation languages. Graphical modeling is another aspect which is used successfully. However, still possibilities exist for use of tailorable templates for advanced modeling (Ören, 1991).

3.2 Model-base Management

Model-based modeling assures realization of management of model specifications as opposed to the management of computerized expressions of models; hence, it facilitates efficiency, reliability, reusability, and interoperability of models. Some additional issues are semantic search of models and especially model integrity.

3.3 Model Processing

As shown in Table 5, model processing consists of: model analysis, model transformation, and behavior generation. From a pragmatic point of view, they can be applicable in model-based simulation where models are expressed in terms of appropriate mathematical systems theories that provide solid methodologies to specify models as well as to process them. Next generation of powerful model-based simulation environments can be realized by an integrative use of several model-based activities.

3.3.1 Model Analysis

There are two types of model analysis: descriptive and evaluative analyses. Descriptive model analysis is model characterization. Evaluative model analysis is model evaluation. As seen in Table 8, model characterization consists of model comprehensibility and model useability

Table 8. Types of **Descriptive Model Analysis**

Model characterization
(Descriptive model analysis) for
- **model comprehensibility**
  - model documentation
    - static model-documentation
    - dynamic model-documentation
  - model ventilation (to examine its assumptions, deficiencies, limitations, etc.)
- **model useability**
  - model referability
    - model-base management
      - model integrity
  - model composability
  - model modifiability

Table 9 summarizes model evaluation, or evaluative analysis of models.

Table 9. Types of **Evaluative Model Analysis**

Model evaluation (Evaluative model analysis) with respect to:
- **modeling formalism** - consistency of model representation - static structure of - component models - total system (coupled model, model of system of systems) - dynamic structure - state transitions, output function(s) - stuctural change - model robustness
- **another model** (model comparison) - structural model comparison - model verification (comparison of a computerized model with its speciafication) - checking - model homomorphism - model isomorhism - model equivalencing for: - any two models - a simplified and original model - an elaborated and original model - behavioral model comparison (comparison of behaviors of several models within a given scenario)
- **real system** - model qualification - model realism (model veracity, model verisimilitude) - adequacy of model structure - static structure (relevant variables, interface of models) - dynamic structure - adequacy of model constants and parameters - model identification - model fitting - model calibration - model correctness analysis - dimensional analysis - model validity - (see Table 3 for types of validity)
- **goal of the study** - model relevance - domain of intended application(s) (appropriate use of a model) - range of applicability of a model - acceptability of a model with respect to its technical system specification

Validity, as a special type of model evaluation, has several types as shown in Table 10. In a glossary of validation, one can list the definitions of each one of the terms given in Table 10. However, an ontology-based dictionary for these terms would have two superiorities: (1) It can also provide the logical relationships of the terms since it will be based on a classification of the concepts and (2) the terms can be linked from a regular alphabetical list. For examples of ontology-based dictionaries, see Ören (2006b), and Ören, Ghasem-Aghaee, and Yilmaz (2007).

Table 10. Types of **Validity**

absolute validity	model validity
conceptual validity	multistage validity
convergent validity	operational validity
cross validity	parameter validity
cross model validity	partial validity
data validity	predictive validity
dynamic validity	predictive model validity
empirical validity	replicative validity
event validity	statistical validity
experimental validity	strict validity
external validity	structural validity
face validity	structural model validity
full validity	submodel validity
gradual validity	technical validity
historical validity	theoretical validity
historical-data validity	time-series validity
hypothesis validity	validity
internal validity	variable validity
logical validity	

Similarly, verification, as a special type of model evaluation, has several types, as shown in Table 11. In this case also, an ontology-based dictionary can display not only the definitions of each of the terms but their logical relationships.

Table 11. Types of **Verification**

black box verification
code verification
correctness verification
data verification
design verification
formal verification
functional verification
independent verification and validation
logical verification
model verification
model-based verification
program verification
verification
verification of conceptual model

3.3.2 Model Transformation

Model transformation, as shown in Table 12 consists of model copying, model reduction, model pruning, model simplification, model elaboration, model isomorphism, model homomorphism, and model endomorphism.

Table 12. Types of **Model Transformation**

Model transformation
- Model copying
- Model reduction
- Model pruning
- Model simplification
- Structural model simplification
- Behavioral model simplification
- Model elaboration
- Model isomorphism
- Model homomorphism
- Model endomorphism

3.3.3 Behavior Generation

In a simulation process, the model is driven by a behavior generator, under the experimental conditions to generate the model behavior. Depending on the emphasis, the behavior generator can also be named the simulation engine or the simulator as it is the case in the terminology used by B.P. Zeigler, 1984.) So long as there is no ambiguity, the choice of the terminology is immaterial. However, since the term "simulator" is widely used for other devices such as airplane simulators or in terms such as "virtual simulators," the more descriptive term "behavior generator" is used in this article.

As seen in Table 13, behavior can be generated by numerical or non-numerical techniques. Numerical techniques for especially continuously models are treated by Cellier and Kofman (2006). Non-numerical techniques are used in artificial intelligence applications to M&S. There are three types of model behavior: point behavior, trajectory behavior, and structural behavior. Generations of trajectory and structural behaviors correspond to trajectory and structural simulations, respectively.

Table 13. Types of Behavior Generation

Behavior generation
- by
- numerical techniques
- non-numerical techniques
- types of model behavior
-point behavior
- computation
- optimization
- search
- trajectory behavior
- simulators
- simulation
- intermittent simulation
- optimizing simulation
- gaming simulation
- structural behavior
- growth systems
- Lindenmeyer systems (L-systems)
- mixed behavior
- mixed trajectory & structural behavior

Point behavior: This is the behavior of static models; i.e., models whose behavior does not depend on time. Experimentation with static models is not simulation. Computation, optimization, and search are examples where the result (behavior) is point behavior. Point behavior can be scalar or n-dimensional vector.

Trajectory behavior: Most simulations do belong to this category where trajectories of descriptive variables are generated. At the end of a simulation study, trajectory behavior can be reduced to a performance index. Some possibilities are: simulators, several types of simulation and intermittent simulation such as optimizing simulation and gaming simulation.

Structural behavior: In some studies, the evolution of the structure of a system can be generated by simulation techniques. Such systems include for example, growth systems for which L-systems or Lindenmeyer systems provide a solid background. Some other applications include, for example, spread of oil spills, forest fires, epidemics, and rumor.

Mixed behavior: Some possibilities are mixed trajectory and structural behavior

4. CONCLUSIONS

Model-based simulation is already a mature discipline to solve many important and complex problems. It is a prime candidate to become a critical national priority in security as well as economic well-being of post-industrial countries (Waite 2006).

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Author Biography

Dr. Ören is a professor emeritus of Computer Science at the University of Ottawa since 1996 where he worked since 1971. His current **research** activities include (1) advanced M&S methodologies such as: multimodels, multisimulation (to allow simultaneous simulation of several aspects of systems), and emergence; (2) agent-directed simulation; (3) cognitive simulation (including simulation of human behavior by fuzzy agents, agents with dynamic personality and emotions, agents with perception, anticipation, and understanding abilities); and (4) reliability and quality assurance in M&S and user/system interfaces. He has also contributed in Ethics in simulation, M&S Body of Knowledge, and multilingual M&S dictionaries. He is the founding director of the M&SNet of SCS. He has over 350 **publications** (some translated in Chinese and German) and has been active in over 350 **conferences** and seminars held in 30 countries. He received SCS Distinguished Service Award (2006) and plaques and certificates of appreciation from organizations including ACM, AECL, AFCEA, and NATO; and is recognized by IBM Canada as a Pioneer of Computing in Canada (2005).