The Richness of Modeling and Simulation and an Index of Its Body of Knowledge

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Abstract. The richness of modeling and simulation (M&S) and its increasing importance are emphasized. The three aspects of professionalism as well as stakeholders of M&S are documented. Work being done by the author on M&S body of knowledge (BoK) is outlined. Several other BoK and M&S BoK studies are referred to. The conclusions section includes the emphases that wide-spread application and ever increasing importance of modelling and simulation necessitate an agreed on body of knowledge index and its elaboration as well as the preservation of the integrity of the M&S discipline.

Keywords: Richness of Modeling and Simulation, Importance of Modeling and Simulation, Simulation Body of Knowledge Index, Simulation Terminology, Exascale Simulation, Ethics in Simulation.

1 Introduction

Modeling and simulation (M&S) discipline provides a powerful and vital infrastructure for many disciplines as well as for large number of application areas [1]. M&S –like mathematics– has its own core knowledge which benefits from appropriate research and development and is also essential for many disciplines.

Several aspects of the richness and comprehensiveness of M&S are elaborated in section 2. In section 3, clarification of some aspects of the importance of M&S is offered. In section 4, the importance of the synergy of M&S and education is highlighted. Aspects of professionalism in as well as stakeholders of M&S are reviewed in sections 5 and 6. The importance of M&S necessitates development of a proper body of knowledge (BoK) index. In section 7, highlights of an Index of an M&S body of knowledge study is given. Section 8 consists of the conclusions and future work. Two indices complete the chapter: A list of over 500 terms denoting several types of simulation as a testimony of the richness of the M&S discipline and an M&S BoK index being developed by the author.

2 Richness of M&S

Compared to some traditional disciplines such as mathematics, physics, and astronomy, modeling and simulation is a young discipline. However, it has been

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maturing steadily [2]. Several articles and book chapters depict comprehensive views of many aspects of M&S [3-5]. A recent article provides a systematic collection of about 100 definitions of M&S and emphasizes some of the many aspects of M&S [6]. Another article offers a critical review of the definitions and shows that some of the legacy definitions are not appropriate anymore [7].

Two aspects of simulation are particularly important: experimentation and experience. From the point of view of *experimentation*, "Simulation is performing goal directed experiments with models of dynamic systems" [7]. A taxonomy of experiments as well as some additional clarifications about experiments are also given by Ören [7]. From the point of view of *experience*, simulation is providing experience under controlled conditions for training or for entertainment. For *training* purposes, simulation is providing experience under controlled conditions for gaining / enhancing competence in one of the three types of skills: (1) motor skills (by virtual simulations), (2) decision and/or communication skills (by constructive simulations; serious games), and (3) operational skills (by live simulations)" Ören [7]. For *amusement* purposes: "Simulation is providing experience for entertainment purpose (gaming simulations). Some aspects of gaming simulation make it a source of inspiration for education as well as for serious games used for training purposes. These aspects include advanced visualization techniques and specification of environments and scenarios. Gaming simulation can also be combined to explore experimentation for scientific research. An example is eyewire project of MIT which is gamified for crowdsourcing to have large cooperation of simulation game players to explore how connectomes of retina work [8-9].

M&S has many other aspects, each of which covering a wealth of concepts [10]. However, in this chapter, only the aspects pertinent to experimentation and experience for training purposes are elaborated on. As a testimony of the richness of simulation, we can cite a large number of types of simulation as well as M&S terms. In Appendix 1, one can see over 500 terms which denote mostly application area-independent types of simulation. An ontology-based dictionary of these terms is planned to be developed. An ontology-based dictionary is a relational dictionary built on top of a taxonomy of the terms. An example is an ontology-based dictionary of terms of machine understanding where over 60 terms are covered [11].

Another evidence of the richness of the M&S discipline is the number of terms it uses. An early trilingual (English-French-Turkish) modeling and simulation dictionary that the author was involved included about 4000 terms [12]. A bilingual (Chinese-English, English-Chinese) version prepared with 30 Chinese contributors has over 9000 terms [13].

3 Importance of M&S

M&S provides very important infrastructure for hundreds of application areas in science, engineering, social as well as health sciences. In this chapter, the importance of M&S is elaborated in three sets of disciplines, i.e., simulation-based science and engineering, simulation-based social sciences, and computational neuroscience. Several other fields, such as simulation-based (civilian as well as military) training and simulation-based learning benefit from the contribution of simulation.

Possibilities that extreme scale simulation offers, provide another dimension to the importance of M&S.

3.1 The Impact of Extreme Scale Computing on Simulation

Extreme scale computers are high-speed computers such as teraflop, petaflop, or exaflop computers. They perform, respectively, 10^{12} (i.e., one thousand times one billion), 10^{15} (i.e., one million times one billion), or 10^{18} (i.e., one billion times one billion) floating point operations per second. Simulations performed on these types of computers are called, extreme-scale simulation, terascale simulation, petascale simulation, or exascale simulation, respectively.

Simulation on exascale computer –or exascale simulation in short– is anticipated to contribute mainly in the following application areas: aerospace, airframes and jet turbines, astrophysics (including cosmology and the nature of dark energy and black holes); biological and medical systems, climate and weather, energy (including combustion, nuclear fusion, solar energy, and nuclear fission), materials science, national security, socioeconomic modelling; and in the following technical areas: mathematics and algorithms, software, hardware, and cyber infrastructure [14].

The ASCAC report also examines what applications may be transformed by going to the exascale simulations [14, p. 25]:

> "*From biology to nuclear engineering, computing at the exascale promises dramatic advances in our capabilities to model and simulate complex phenomena, at levels of fidelity that have the potential to dramatically change both our understanding and our ability to comprehend. Thus, there are almost certain to be great benefits to going to the exascale*" [14].

While exaflop computers are in active research and development, petaflop supercomputers already exist. As of November 2011, "*Japan's K Computer maintained its position atop the newest edition of the TOP500 List of the world's most powerful supercomputers, thanks to a full build-out that makes it four times as powerful as its nearest competitor. Installed at the RIKEN Advanced Institute for Computational Science (AICS) in Kobe, Japan, the K Computer achieved an impressive 10.51 petaflop/s . . . in second place is the Chinese Tianhe-1A system with 2.57 petaflop/s performance*" [15]. As a practical importance of petascale simulation, one can point out that, if one billion entities are represented in a simulation model, every second, over a million operations can be performed for each object represented.

3.2 Simulation-Based Science and Engineering

Simulation-based engineering science (SBES) is a well established and important concept [16]. The major findings and principal recommendations show the crucial importance of simulation in all branches of engineering and engineering applications:

> "*SBES is a discipline indispensable to the nation's continued leadership in science and engineering. It is central to advances in biomedicine, nanomanufacturing, homeland security, microelectronics, energy and environmental sciences, advanced materials, and product development. There is ample evidence that*

developments in these new disciplines could significantly impact virtually every aspect of human experience." [16, p. xvi]. "*Meaningful advances in SBES will require dramatic changes in science and engineering education*" [16, p. 56].

Interested readers may benefit reading the report. Here, some points from the conclusions part of the report are highlighted:

"First, computer modeling and simulation will allow us to explore natural events and engineered systems that have long defied analysis, measurement, and experimental methodologies, . . .

Second, modeling and simulation will have applications across technologies—from microprocessors to the infrastructure of cities.

. . .

Fifth, modeling and simulation will expand our ability to cope with problems that have been too complex for traditional methods. . . .

Sixth, modeling and simulation will introduce tools and methods that apply across all engineering disciplines—electrical, computer, mechanical, civil, chemical, aerospace, nuclear, biomedical, and materials science. . . .

3.3 Simulation-Based Social Sciences

Simulation-based social sciences include anthropology, archaeology, economics, geography, government, linguistics, management, political science, and sociology. The interest areas of simulation-based social sciences of the Centre for Research on Simulation in the Social Sciences (CRESS) [17] are specified as follows:

"Simulation is a novel research method in most parts of the social sciences, including sociology, political science, economics, anthropology, geography, archaeology and linguistics. It can also be the inspiration for new, process-oriented theories of society."

A selection from the aims of World Congress on Social Simulation (WCSS 2012) [18] reads as follows:

"Social sciences are moving in a direction in which their various constituent parts are sharing a common set of foundations, languages and platforms, which makes the social sciences be unprecedentedly behavioral, algorithmic and computational. At the turn of the 21st century, a group of computer scientists and social scientists worked together to initiate new series of conferences and to establish new academic organizations to give momentum to this emerging integration now known as computational social sciences. . . . WCSS is sponsored by the three regional scientific associations on social simulations:" The European Social Simulation Association (ESSA) [19], Pacific Asian Association for Agent-based Approach in Social Systems Sciences (PAAA) [20] and Computational Social Science Society of the Americas (CSSSA) [21].

3.4 Computational Neuroscience

Computational neuroscience is a subfield of neuroscience that uses mathematical methods to simulate and understand the function of the nervous system [22]. "A connectome is a comprehensive map of neural connections in the brain" [23]. "The Human Connectome Project aims to provide an unparalleled compilation of neural data, an interface to graphically navigate this data and the opportunity to achieve never before realized conclusions about the living human brain" [24]. Advanced simulation is an integral part of the connectome project. A recent article about the Neuropolis project, to be centered in Switzerland and preselected by European Union, presents it as the future capital of the virtual brain [25].

4 M&S and Education

An important corollary of the importance of M&S is proper education and training in modeling and simulation at every level, starting at primary and secondary education to be followed by education at colleges and universities at undergraduate, graduate, and post graduate levels. Vocational training in modeling and simulation is also of particular importance. There are already several graduate M&S degree programs to educate future simulationists. However, for future professionals such as all types of engineers, scientists, including social scientists, proper M&S education will definitely be an asset [26-27]. It is expected that the education of future policy makers and public administrators may also benefit from several possibilities simulation offer. Lack of proper simulation-based professional training may even be invitation to disasters. A recent contribution to university-level education in M&S with several current references is done by Mielke et al. [28]. Another slightly dated report describes the contents of a Microsoft Access database developed in support of the Workforce Modeling and Simulation Education and Training for Lifelong Learning project. The catalogue contains searchable information about 253 courses from 23 U.S. academic institutions" [29].

5 Aspects of Professionalism in M&S

Three aspects of professionalism in M&S are activities, knowledge, and conduct and monitoring [30].

M&S Activities. Three groups of activities are involved in professionalism of M&S. (1) Generation of products, services, and/or tools to solve problems. This is normally done by industry. M&S activities also include generation of simulation-based solutions. (2) Generation & dissemination of knowledge. This is normally done by academia and R&D establishments. (3) Funding which is done by owner(s) of the project, governmental agencies, users, or interest groups.

Knowledge. Five types of knowledge are needed for professional M&S activities. (1) The core knowledge of the M&S discipline, i.e., M&S Body of Knowledge (M&S BoK). It is elaborated in section 7 and an Index being developed by the author is given as Appendix 2. (2) Knowledge of relevant Science (including system science), Engineering (including systems engineering), and Technology. (3) Knowledge of business and industry. (4) Knowledge of application area(s). (5) Knowledge of how to behave, i.e., code of professional ethics (Simulation_ethics).

Monitoring and Certification. Two types of monitoring are needed. (1) Professional and ethical conduct (both voluntary (responsibility) and required (accountability)). (2) Certification of professionalism of: (2.1) Individuals, as M&S professionals, (2.2) Companies for their maturity levels (yet to be specified). (3) Educational programs and institutions.

6 Stakeholders of M&S

M&S stakeholders include individuals, institutions, discipline and market, and countries [30].

Individuals include: Researchers/educators, practitioners, experienced as well as novice learners, customers and users of products/services, people (to be) affected by simulation projects (done or not yet done), industrialists, and technicians.

Institutions include: Customer or user organizations (that may be government organizations as well as profit and non-profit organizations), agencies for licensing or certification of individuals and organizations, funding agencies, professional societies, standardization organizations, educational institutions, industrial or professional groups and centers, and commercial organizations. The fact that there are over 100 associations and well over 40 groups and centers is also a good indicator of the variety of stakeholders of M&S [31].

Discipline and Market

Countries. A higher level stakeholder is "countries" which may have or may acquire leading edge superiority over other countries by exploring possibilities offered by extreme scale simulation, especially by exascale simulation. But not limited to this possibility alone.

7 M&S Body of Knowledge

7.1 M&S Bok: Preliminary

A body of knowledge (BoK) of a discipline is “structured knowledge that is used by members of a discipline to guide their practice or work” [32]. "While the term *body of knowledge* is also used to describe the document that defines that knowledge – the *body of knowledge* itself is more than simply a collection of terms; a professional reading list; a library; a website or a collection of websites; a description of professional functions; or even a collection of information. It is the accepted ontology for a specific domain" [33]. It is worthwhile underlining the fact that a BoK of a specific domain or discipline is its ontology. This fact necessitates that the development of a BoK should be systematic. A BoK Index is a set of systematically organized pointers to the content of a BoK. Desired BoK Index features include: *"(1) Supporting a variety of users within the M&S Community of Practice (CoP). (2) Identifying and providing access to BoK topics/content. (3) Providing configuration managed views to content that changes over time*" [34].

7.2 Bok of Other Disciplines

It would be useful to have an idea about the body of knowledge studies of other disciplines. Over 30 such BoK and their URLs are listed at the M&S BoK website being developed and maintained by Ören [35]. These BoK studies are grouped under the following categories: Business/Management, Civil Engineering, Database, Family and Consumer Sciences, Geography, Mechanical Engineering, Medicine, Project Management, Quality, Research Administration, Safety, Software Engineering / Computer Science, Systems Engineering, Usability, and Utility Infrastructure Regulation. Given that many of these disciplines/fields have more than one BoK is indicative that M&S may also have more than one BoK. This requirement may stem especially from the domain of application. However, at a higher level, the identification of a comprehensive view of M&S and elaboration of several of its aspects may be useful to avoid the problems of having narrow vision.

7.3 M&S Bok: Previous and Ongoing Studies/Activities

Previous M&S BoK studies, developed by domain experts cast light on several aspects of M&S [36-40]. A recent M&S BoK is developed for DoD [41]. As a distinguishing feature from a large number of BoK studies of other disciplines, the M&S BoK developed for DoD combines Bloom's taxonomy of learning with the BoK. However, the combination of the M&S BoK with Bloom's taxonomy detracts the attention from what is the core knowledge of M&S and confuses them with the levels of knowledge needed by different categories of users.

7.4 M&S Bok Being Developed by the Author

A website has been developed and maintained by Ören for an M&S BoK Index [35]. Some of the work done by Ören –alone or with colleagues– include the following [30, 36, 42-45]. The M&S BoK being developed by Ören consists of six parts: Background, core areas, supporting domains, business/industry, education/training, and relevant references [35] and is given as Appendix 2. Especially the Business/Industry section benefited from the previous work [46].

8 Conclusions and Future Work

M&S provides a vital infrastructure for large number of disciplines and application areas. With the advancements in high-speed computers, new vistas are being opened for M&S to tackle problems which would be unimaginable a few decades ago. The synergy of systems engineering, software agent and M&S opens new possibilities for advanced simulation [47]. The richness of the M&S field is well documented by its many types, by its own rich and discriminating terminology, and by the content of the M&S BoK studies.

Theoretical basis of M&S was laid down by Zeigler [48]. The Discrete Event System Specification (DEVS) formalism that he created is a well established theoretical basis for discrete event system simulation and has already many varieties [49]. There are many other publications about theories of simulation models, e.g., Barros [50]. A recent article elaborates on some aspects of axiomatic system theoretical foundations of M&S [51].

A multilingual (English-French-Italian-Spanish-Turkish) M&S dictionary is being developed by international co-operation of over 70 simulationists [52]. (M&S dictionary project). The author is committed to enhance the M&S BoK study that he started; and already an invitation for the final phases of its preparation is open [45]. Wide-spread application and ever increasing importance of modelling and simulation necessitate the preservation of its integrity. The word integrity is used as defined in Merriam-Webster: "an uncompromising adherence to a code of moral, artistic, or other values**:** utter sincerity, honesty, and candor**:** avoidance of deception, expediency, artificiality, or shallowness of any kind." Such code of ethics already exists for simulation and is adopted by many concerned groups [53]. It is expected that the list of adherent groups will grow.

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Appendix 1

Over 500 terms denoting several types of simulation

3d simulation
A--
ab initio simulation
abstract simulation
academic simulation
accurate simulation
activity-based simulation
ad hoc distributed simulation
adaptive simulation
adaptive system simulation
adiabatic system simulation
advanced simulation
advanced distributed simulation
advanced numerical simulation
agent simulation
agent-based simulation
agent-based participatory simulation
agent-controlled simulation
agent-coordinated simulation
agent-directed simulation
agent-initiated simulation
agent-monitored simulation
agent-supported simulation
aggregate level simulation
autotelic system simulation
B--
backward simulation
base case simulation
baseline simulation
bio-inspired simulation
biologically-inspired simulation
bio-nano simulation
block-oriented simulation
bond-graph simulation
branched simulation
built-in simulation
C--
case-based simulation
cellular automaton simulation
classical simulation
closed-form simulation
closed-loop simulation
cloud simulation
cloud-based simulation
cluster simulation
coercible simulation
cognitive simulation
cokriging simulation
computer-aided simulation
computer-based simulation
computerized simulation
computer-mediated simulation
concurrent simulation
condensed-time simulation
conditional simulation
conjoint simulation
conservative simulation
constrained simulation
constructive simulation
constructive training simulation
continuous simulation
continuous-change simulation
continuous-system simulation
continuous-time simulation
conventional simulation
convergent simulation
cooperative hunters simulation
cooperative simulation
coopetition simulation
co-simulation
coupled simulation
credible simulation

AI-controlled simulation	collaborative component-based simulation	critical event simulation
AI-directed simulation	collaborative distributed simulation	customizable simulation
all software simulation	collaborative simulation	customized simulation
all-digital simulation	collaborative virtual simulation	**D--**
all-digital analog simulation	collocated cokriging simulation	data-driven simulation
allotelic system simulation	collocated simulation	data-intensive simulation
analog simulation	combined continuous-discrete simulation	decision simulation
analog computer simulation	combined simulation	degree 1 simulation
analytic simulation	combined system simulation	degree 2 simulation
anticipatory perceptual simulation	competition simulation	degree 3 simulation
appropriate simulation	component simulation	demon-controlled simulation
approximate simulation	component-based collaborated simulation	descriptive simulation
approximate zero-variance simulation	component-based distributed simulation	detached eddy simulation
as-fast-as-possible simulation	composable simulation	deterministic simulation
asymmetric simulation	composite simulation	DEVS simulation
asynchronous simulation	compressed-time simulation	digital analog simulation
audio simulation	computational simulation	digital computer simulation
augmented live simulation	computer network simulation	digital quantum simulation
augmented reality simulation	computer simulation	digital simulation
direct numerical simulation	exascale simulation	hands-on simulation
direct simulation	expanded-time simulation	hardware-in-the-loop simulation
disconnected simulation	experience-aimed simulation	heterogeneous simulation
discrete arithmetic-based simulation	experiment-aimed simulation	hierarchical simulation
discrete event line simulation	experimental simulation	high-fidelity simulation
discrete event simulation	explanatory simulation	high-level simulation
discrete simulation	exploration simulation	high-resolution simulation
discrete-change simulation	exploratory simulation	historical simulation
discrete-system simulation	ex post simulation	HLA-based simulation
discrete-time simulation	extensible simulation	HLA-compliant simulation
distributed agent simulation	extreme scale simulation	holographic simulation
distributed DEVS simulation	**F--**	holonic simulation
distributed interactive simulation	fast simulation	holonic system simulation
distributed real-time simulation	fault simulation	HPC simulation
distributed simulation	fault tolerant simulation	human-centered simulation
distributed web-based simulation	faulty simulation	human-in simulation
distributed-parameter system simulation	federated simulation	human-in-the-loop simulation
DNA-based simulation	first degree simulation	human-machine simulation
dynamic simulation	full system simulation	hybrid computer simulation
dynamic system simulation	fully coupled simulation	hybrid gaming simulation
dynamically composable simulation	functional simulation	hybrid simulation
E--	fuzzy simulation	**I--**
electronic gaming and simulation	fuzzy system simulation	identity simulation

embedded simulation
emergence simulation
emergent simulation
enabling simulation
endomorphic simulation
engineering simulation
entertainment simulation
entity-level simulation
error-controlled simulation
escapist simulation
ethical simulation
evaluative simulation
event-based agent simulation
event-based discrete simulation
event-based simulation
event-driven simulation
event-following simulation
event-oriented simulation
event-scheduling simulation
evolutionary simulation
evolutionary system simulation
ex ante simulation
introspective simulation
inverse ontomimetic simulation

J--

joint simulation

K--

knowledge-based simulation
kriging simulation

L--

laboratory simulation
large-scale simulation
large eddy simulation
lazy simulation
lean simulation
legacy simulation
library-driven simulation
linear programming embedded simulation
linear system simulation
line-of-sight simulation
linkage to live simulation
live simulation
live training simulation
live system-enriching simulation

G--

game simulation
game-like simulation
game-theoretic simulation
gaming simulation
Gaussian simulation
general purpose distributed simulation
generalized simulation
generative parallax simulation
generative simulation
generic simulation
genetic algorithm simulation
goal-directed system simulation
goal-generating system simulation
goal-oriented system simulation
goal-processing system simulation
goal-setting system simulation
graphical simulation
grid simulation
grid-based simulation

H--

hand simulation
microsimulation
mirror simulation
mirror world simulation
mission rehearsal simulation
mixed simulation
mixed-signal simulation
mobile simulation
mobile-device activated sim
mobile-device initiated simulation
mobile-device triggered simulation
mock simulation
modular simulation
Monte Carlo simulation
multi-agent participatory simulation
multi-agent simulation
multi-agent-based simulation
multi-agent-supported simulation
multiaspect simulation
multilevel simulation
multimedia simulation
multimedia-enriched simulation
multi-paradigm simulation

immersive simulation
impact of simulation
importance-sampling-based simulation
in silico simulation
in vitro simulation
in vivo simulation
inappropriate simulation
in-basket simulation
incremental simulation
individual-based simulation
inductive simulation
industrial scale simulation
instructional simulation
integrated simulation
intelligent simulation
intelligent system simulation
interactive simulation
intermittent simulation
interoperable simulation
interpretational simulation
interpretive simulation
interval-oriented simulation
non-line-of-sight simulation
non-numerical simulation
non-trial simulation
non-yoked simulation
non-zero sum simulation
normative simulation
not perceptual simulation
numerical simulation

O--

object-oriented simulation
online role-play simulation
online simulation
ontology-based agent simulation
ontology-based multiagent simulation
ontology-based simulation
ontomimetic simulation
open-form simulation
open-loop simulation
optimistic simulation
object-oriented simulation
online role-play simulation
optimizing simulation

live system-supporting simulation
logic simulation
logical simulation
low level simulation
Lindenmayer system simulation
L-system simulation

M--
machine simulation
machine-centered simulation
man-centered simulation
man-in-the-loop simulation
man-machine simulation
man-machine system simulation
manual simulation
Markov simulation
massively multi-player simulation
mathematical simulation
mental simulation
mesh-based simulation
mesoscale simulation
microanalytic simulation
microcomputer simulation
multiphysics simulation
multi-player simulation
multiple-fidelity simulation
multi-processor simulation
multirate simulation
multiresolution simulation
multiscale simulation
multi-simulation
multistage simulation
mutual simulation

N--
nano simulation
nano-scale simulation
narrative simulation
nested simulation
net-centric simulation
networked simulation
network-oriented simulation
non-convergent simulation
non-deterministic simulation
non-equation-oriented simulation
non-linear system simulation
ordinary kriging simulation
outcome-driven simulation
outcome-oriented simulation

P--
parallax simulation
parallel discrete-event simulation
parallel simulation
parallelized simulation
partial equilibrium simulation
participative simulation
participatory agent simulation
participatory simulation
peace simulation
peer-to-peer simulation
perceptual simulation
petascale simulation
Petri net simulation
physical simulation
physical system simulation
portable simulation
predictive simulation
prescriptive simulation

process simulation
process-based discrete event simulation
process-oriented simulation
proof-of concept simulation
proxy simulation
pseudosimulation
public domain simulation
pure software simulation
purpose of simulation

Q--
qualitative simulation
quantitative simulation
quantum simulation
quasi-analytic simulation
quasi-Monte Carlo simulation

R--
random simulation
rare-event simulation
real-system enriching simulation
real-system support simulation
real-time continuous simulation
self-organizing system simulation
self-replicating system simulation
self-stabilizing system simulation
semiotic simulation
sequential Gaussian simulation
sequential simulation
serial simulation
serious simulation
service-based simulation
shape simulation
simulation
simultaneous simulation
single-aspect simulation
single-component simulation
single-processor simulation
skeleton-driven simulation
smart phone activated simulation
smoothness simulation
spatial simulation
spreadsheet simulation
stand-alone simulation
teleonomic system simulation
terminating simulation
texture simulation
third degree simulation
thought controlled simulation
thought experiment simulation
thought simulation
throttled time-warp simulation
time-driven simulation
time-slicing simulation
time-stepping simulation
time-varying system simulation
time-warp simulation
trace-driven simulation
tractable simulation
training simulation
trajectory simulation
transfer function simulation
transparent reality simulation
trial simulation
trustworthy simulation

real-time data-driven simulation
real-time decision making simulation
real-time simulation
reasonable simulation
reasoning simulation
recursive simulation
regenerative simulation
regenerative simulation
related simulation
reliable simulation
remote simulation
replicative simulation
retro-simulation
retrospective simulation
reverse simulation
risk simulation
role playing simulation
role-play simulation
rule-based simulation
rule-based system embedded simulation

S--

scalable simulation
scaled real-time simulation
scientific simulation
second degree simulation
self-organizing simulation
wearable computer-based simulation
wearable simulation
Web service-based simulation
Web-based simulation
static simulation
steady-state simulation
stochastic simulation
strategic decision simulation
strategic simulation
strategy simulation
strong simulation
structural simulation
structure simulation
successor simulation
suitable simulation
swarm simulation
symbiotic simulation
symbolic simulation
symmetric simulation
system simulation
systematic simulation
system-of-systems simulation
systems-theory-based simulation

T--

tactical decision simulation
tactical simulation
tandem simulation
technical simulation
teleogenetic system simulation
teleological system simulation
Web-centric simulation
Web-enabled simulation
yoked simulation

U--

ultrascale simulation
uncertainty simulation
unconstrained simulation
uncoupled simulation
unified discrete and continuous simulation
unsuitable simulation
utilitarian simulation

V--

variable fidelity simulation
variable resolution simulation
very large eddy simulation
very large simulation
video game simulation
virtual simulation
virtual time simulation
virtual training simulation
virtualization simulation
visual interactive simulation
visual simulation

W--

war simulation
warfare simulation
weak classical simulation
weak simulation

Z--

zero-sum simulation
zero-variance simulation

Appendix 2

Modeling and Simulation Body of Knowledge (M&S BoK) Index

(adopted from M&S BoK-Ören which is being updated)

- Background
- Core Areas
- Supporting Domains
- Business/Industry
- Education/Training
- References

Background

1. Preliminary

1.1 **Approach to the preparation of the Index**

1.2 **Version history**

1.3 **Members of the review committee**

1.4 **Recommendations and how they have been taken into account**

2. Introduction

2.1 Aspects and basic definitions of simulation

2.2 Scope of the study

2.3 Stakeholders of M&S

2.4 M&S associations, groups, and centers

2.5 Why an M&S BoK? Rationale and possible usages

2.6 Importance of M&S

2.7 High level recognition of M&S

3. Terminology

3.1 **Some definitions of M&S (and their critical reviews)**

3.2 Dictionaries of M&S

3.3 **Ontology-based dictionaries (what? examples, benefits)**

4. Comprehensive View

4.1 **Challenges and benefits of comprehensive view (Big picture) of M&S**

Core Areas

1. Science/Methodology of M&S

1.1 Data

- *Issues (types of data and related terms)*
- *Variables* **(types of variables and related terms)**
  - **-Input variables (types of input values and related terms)**
- *Values* **(types of values and related terms)**

1.2 Models

- *Dichotomy of reality and its representation (model)*
- *Models and modeling*
  - *-Conceptual models, conceptual modeling*
  - *-Model attributes: fidelity, (multi-)resolution, scaling*
  - *-Modeling formalisms: Discrete, cellular, continuous*
  - *-Model composability, dynamic model composability*
  - *-Modelling physical systems*
  - *-Visual models*
  - *-Modeling qualitative systems*
  - *-Types of models and related terms*
  - *-Taxonomies of simulation formalisms and simulation models*
- *Model building (model synthesis)*
  - *-Modeling issues: reusability*

-Model composition (and dynamic model composition)

- *Model-base management*

  -Model search (including semantic model-search)

- *Model parameters and parameter-base management*

  -Parameters, **auxiliary parameters (deterministic/stochastic)**

- *Model characterization (Descriptive model analysis)*

  -For model comprehensibility

  --Model documentation (static/dynamic)

  --Model ventilation
  (to examine assumptions, deficiencies, limitations)

  -For model usability (model referability)

- *Model evaluation (Evaluative model analysis) with respect to*

  -a modelling formalism

  --Model consistency with respect to a modeling formalism

  --Model robustness

  -another model

  --Structural model comparison
  (model verification, checking, equivalencing)

  -real system (for analysis problems)

  --Model validity

  -technical system specification (for design and control problems)

  --Model qualification
  (model realism, adequacy, correctness analysis)

  -goal of the study -Model relevance

  --Model relevance

- *Model transformation*

  -Types of model transformation

  (copying, elaboration, reduction (simplification, pruning), isomorphism, homomorphism, endomorphism)

1.3 Experiments

- *Issues related with experiments*

  -Types of experiments

  -Terms related with experiments and experimentation

  -Experimental conditions (experimental frames)

  --Applicability of an experimental frame to a model

  -Experimentation parameters

- *Statistical design of experiments (issues and types)*

  -Computer-aided systems for design of experiments

  -Computer-aided systems for execution of experiments

1.4 Model behavior

- *Main issues related with model behavior*

  -Types of and terms related with model behavior

- *Generation of model behavior (for each modeling formalisms)*

-For discrete event models

-For discrete-time systems
(time-slicing simulation, finite state automata)

-For Petri nets

-For (and piece-wise) continuous-change systems
--Integration, processing discontinuity, stiffness

-For combined discrete/continuous-change systems

• Symbolic behaviour-generation

-Mixed numerical/symbolic behaviour generation

• *Analysis of model behavior*

-Processing and compression of model behavior (analytical, statistical processing)

-Visualization of model behavior (3-D, animation)

1.5 M&S interoperability

• *DIS*

• *ALPS*

• *HLA*

• *TENA*

• *other approaches*

1.6 **Computational intelligence and M&S**

• Agent-directed simulation

-Agent-based models & agent-based modeling

-Agent simulation, Agent-supported simulation

-Agent-monitored simulation, Agent-initiated simulation

• **Soft computing and M&S**

-Neural networks and simulation

-Fuzzy logic and simulation (fuzzy simulation)

-Evolutionary computation and M&S
--Genetic computation and simulation (genetic simulation)
--Swarm intelligence and simulation (swarm simulation)

1.7 Types of simulation
• **Types and terms**
• **Taxonomy of simulations**

1.8 Reliability & Quality Assurance of M&S
• Errors
-Types, terms, taxonomy
• **Validation**
-Types, terms, taxonomy
-Validation techniques and tools
• **Verification**
-Types, terms, taxonomy
-Verification techniques and tools
• **Quality assurance (QA)**
-Basic concepts, Types, terms, taxonomy
-Built in quality assurance
• **Failure avoidance**
-In traditional simulation, in inference engines used in simulation, in cognitive and affective simulations

1.9 Life cycles of M&S

- **For experimentation**
  - -For decision support
    - --Types of simulation-based decision support
  - -For understanding
  - -For education
- **To gain experience for training to enhance**
  - *-Motor skills*
    for civilian/military applications
    (virtual simulation; simulators, virtual simulators)
  - *-Decision making and communication skills*
    for civilian/military applications (constructive simulation – serious games; business gaming, peace gaming, war gaming)
  - *-Operational skills*
    for civilian/military applications (live simulation)
- **(To gain experience) for entertainment (simulation games)**
- *M&S for augmented reality*
- **Synergies of simulation games with other types of simulations**
- **Synergies of M&S with other disciplines**
- *Integrated LVB simulation*
- *Simulation integrated with decision support such as C4I*

2. Technology of M&S

2.1 M&S languages

- Programming languages
- Graphic languages
- Problem specification languages

2.2 M&S tools and environments

- *Human/system interfaces*
  - *-Types of interfaces (including immersion)*
  - *-Characteristics and design principles for human/system interfaces*
    - *--For front end interfaces*
    - *--For back-end interfaces*

2.3 Simulation-based problem solving environments for

- **Science**
- **Engineering**
- **Social sciences**
- **Health sciences**
- Defence

2.4 Infrastructure for M&S

- **M&S standards (By source, by topic)**
- **Lessons learned, codes of best practice**
- **Resource repositories**
  - **-Data, models, algorithms, heuristics, software, hardware**
  - **-Educational material**

3. History of M&S

3.1 Early simulations

3.2 Early simulators

3.3 Evolution of the M&S industry

4. Trends, challenges, and desirable features

4.1 Trends

4.2 Challenges

4.3 Desirable features

Supporting Domains

1. Supporting science areas
- **1.1 System science (as bases for modeling & algorithmic model processing)**
  - **Emergence, emergent behavior**
  - **Complex adaptive systems**
- **1.2 Physics**
- **1.3 Mathematics (numerical analysis, probability, statistics)**
- **1.4 Queueing theory**

2. Supporting engineering areas
- **2.1 Systems engineering (for simulation systems engineering)**
- **2.2 Software engineering**
- **2.3 Visualization (including advanced display techniques)**
- **2.4 Sonorization** (including speech synthesis)

3. Computers
- **3.1 Digital, hybrid, analog; mobile, cloud**
  - Mobile simulation, cloud simulation
- **3.2 Extreme-scale computers (Petascale simulation, Exascale simulation)**
- **3.3 Soft computing and M&S**
  - **Neural networks and simulation**
  - **Fuzzy logic and simulation**
  - **Evolutionary computation and M&S**
    - **-Genetic computation and simulation**
    - **-Swarm intelligence and simulation**

Business/Industry

1. Management of M&S
- **1.1 Levels of M&S management**
  - **Enterprise level (Enterprise management)**
  - **Project level (Project management)**
  - **Product level (Product management)**
- **1.2 Life-cycle span of M&S management**
- **1.3 Resource management**
  - **Personnel management**
  - **Infrastructure management**
  - **Configuration management**
- **1.4 Quality management**
  - **Documentation management (Requirements, versions)**
  - **Uncertainty management**
  - **VV&A management**
  - Failure avoidance management
- **1.5 Cost-schedule management**
- **1.6 Success metrics for M&S management**

2. Types of employment in M&S
- **2.1 M&S for experimentation**
  - **For decision support (including simulation-based engineering)**
    - **-simulation-based acquisition**
  - ***F*or understanding (including simulation-based science)**

- ***F*or education**

2.2 M&S for Training

- ***F*or motor skills (for simulators, virtual simulators)**
- ***F*or decision making and communication skills (for constructive simulation)**
- ***F*or operational skills (for live simulation)**

2.3 M&S for entertainment (simulation games)

2.4 Visualisation for M&S

2.5 Sonorization for M&S

3. Domains of employment of M&S

3.1 Subject areas of applications for M&S

4. M&S business practice and economics

4.1 Economics of M&S

4.2 M&S market description

4.3 M&S-based enterprise

4.4 M&S investment and ROI

4.5 Reuse of M&S assets

4.6 Cost of M&S asset development, use, etc.

4.7 Value of M&S

4.8 Economic impact

5. M&S workforce

5.1 Community of practice

5.2 Workforce development needs / requirements

5.3 Curricular management

5.4 Professional certification for practitioners

6. Maturity levels and certification of:

6.1 Individuals

6.2 Organizations

6.3 Curricula

6.4 Educational programs

7. Ethics for M&S

7.1 Code of professional ethics for simulationists

7.2 Rationale

Education/Training

1. Education for M&S

1.1 Academic programs and curricula (for M&S professionals)

- Undergraduate programs and curricula
- Graduate programs and curricula
- Doctoral programs and curricula

1.2 Non-academic programs

- Executive seminars
- Professional appreciation and development seminars/courses

2. M&S for education

2.1 Academic programs and curricula at:

- *Universities*
  - For service courses in:
    - --Science

--Engineering

--Humanities

• *High schools*

• *Elementary schools*

2.2 General education

• *Continuing education*

• *To inform public*

References

1. M&S resources

1.1 Lists of M&S resources

1.2 M&S bibliographies

1.3 M&S dictionaries, encyclopedia, M&S master plans, standards

1.4 Repositories of educational material

1.5 M&S Archives

• M&S Books, Journals, Proceedings, Reports

1.6 News resources on M&S

• Google (news on simulation)

1.7 M&S Social networks

1.8 M&S blogs

2. References

2.1 by authors

2.2 by topics

• Body of knowledge (BoK)

-BoK of other areas

-M&S BoK – early studies & other contibutions

• Composability, Reusability, Interoperability

• Conceptual Models and Conceptual Modeling

• Economics of M&S

M&S Epistemology, Ontologies, Taxonomies

M&S Lessons Learned - Best Practices

Simulation and Systems Engineering

Simulation Professionals & Needed Qualifications

Validation/Verification

2.3 by application areas