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# DO WE NEED A NATIONAL RESEARCH AGENDA FOR MODELING AND SIMULATION?

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## ABSTRACT

The National Modeling and Simulation Coalition (NMSC) is interested in a national research agenda that enables the convergence of domain specific modeling and simulation (M&S) approaches towards a common discipline to foster reuse and dissemination of research results. This panel evaluates the various views on such an effort from experts in the domains of science, engineering, and applications.

## 1 INTRODUCTION

The National Modeling and Simulation Coalition (NMSC) is the capstone organization to promote and leverage Modeling and Simulation (M&S) to better the human condition and to strengthen the National well - being. The mission of the NMSC is to create a unified national community of individuals and organizations around the M&S discipline and professional practice and to be the principal advocate for M&S. The purpose of the NMSC is to serve the needs of all components of the M&S community of practice in order to expand the use of M&S and to recognize it as a profession, as an industry, and in the marketplace. It provides a forum for dialog across industry, government, academia and professional societies and support for the discipline in the areas of technology/research and development, education/professional development, industrial development, and business practice through a campaign of public awareness. It provides a central channel of communication in order to simplify, expedite, and improve the national consideration of the many policies, regulations, problems, opportunities and questions of broad application involved in the M&S enterprise.

A high priority in this context is to support the convergence of various application domains towards communicable, shareable, applicable, and reusable research. Accordingly, the NMSC started to organize a series of expert panel discussions at events of the M&S community to initialize the discussion on what topics are of general interest. The objective was to identify topics that should make it onto a national research agenda to be distributed to academia, industry, and government. The expert panel conducted at this Winter Simulation Conference addresses this challenge as well, bring experts together that are well known to the audience. The objective of each contribution was to address the state of the art in the domain, identified needs, and how a national research agenda can help to close the identified gaps.

During the NMSC annual meeting in February 2015, M&S as a discipline was discussed as comprising three important components (Padilla, Diallo, and Tolk 2011), as visualized in Figure 1.

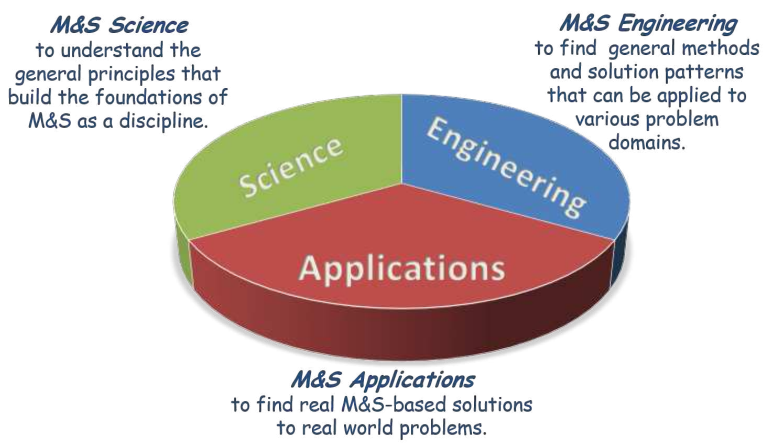


Figure 1: M&S as a Discipline

It was observed that in particular in industry and government the solution side of M&S as a discipline – the M&S Applications – is emphasized. Applications, however, are usually rooted in the taxonomical structures of the supported domain, which makes it hard to share and reuse research results. If common methods are applied that are derived from the M&S Engineering perspective, we already move from multidisciplinary methods to interdisciplinary methods. For the true convergence of technology, common foundations are needed to support general insights from a transdisciplinary perspective (Stock and Burton 2011). Within this panel, we intend to identify candidate research challenges common to various application domains that already are connected to the commonly accepted methods discussed at the Winter Simulation Conferences.

## 2 SIMULATION FOR DECISION SUPPORT AND INSIGHT

Business and management have been using modeling and simulation applications for a long time as part of their portfolio of decision support tools, but not always effectively. Further, a purely quantitative assessment may provide insufficient insight when complex social interactions are present.

### 2.1 Modeling for Business and Management (Nelson)

Stochastic simulation is perhaps the only general-purpose tool that is in wide use for quantifying risk in business and management decisions. Spreadsheet add-ins that facilitate risk analysis—both commercial and free—are readily available, easy to use, and actually are used. Critically, their output displays emphasize the *distribution* of possible future outcomes: that is, they focus on the *risk* of making a decision in an uncertain world.

Risk analysis is somewhat less developed in dynamic, stochastic, systems simulation (i.e., discrete-event simulation, agent-based simulation). This is at least partially because risk analysis in systems simulation is harder: dynamic systems evolve over (possibly) a very long time horizon, are frequently non-stationary, and system optimization is often the goal which means that many (perhaps thousands) of alternative system designs or scenarios are simulated. Discrete-event simulation has its roots in queueing theory, which tends to emphasize long-run average performance measures for stationary stochastic systems, and this history has influenced the default output summaries and displays in many systems simulation products. Of course, animation provides a compelling way to visualize the system's inherent variability, but one can expect only so much patience for viewing lengthy animations from multiple alternative system designs. Systems simulation products all provide *measures of error*, like confidence intervals (CIs) for the long-run average performance; unfortunately, users frequently interpret CIs as *measures of risk* that characterize the variability of possible futures. This misinterpretation is perhaps worse than not quantifying risk at all.

Neither static spreadsheet simulations nor dynamic system simulations fully convey to their users the maxim that *decisions should be based on measures of risk, while experiment design should be based on measures of error.* The field of simulation would benefit from a national research agenda on, and education about, the display and interpretation of simulation output, especially in dynamic settings. The relatively rapid adoption of the measure of risk and error (MORE) plot (Nelson 2008) by products such as Simio and Simul8 illustrates that improvements in this area are possible without imposing a significant burden on simulation software. We also have a timely opportunity to leverage the rapid advances in analytics to support simulation-based risk analysis by making sure that it is easy for simulation software to export detailed sample paths to powerful data analytics tools.

A more difficult problem that has achieved less attention is quantifying and managing simulation *model risk*. "Model risk" refers to the uncertainty in simulation-based results, and therefore simulation-based decisions, due to the model being an imperfect representation of reality. Spreadsheet simulation software, and some systems simulation software, include basic sensitivity analysis that can be helpful in this regard. However, even when a simulation model is sensitive to a particular parameter, if that parameter is well known or estimated precisely, then high sensitivity engenders little decision-making risk. Thus, sensitivity analysis alone is not enough. Also, simulation-based prediction of which system design is best may be less affected by model risk than simulation-based prediction of the actual outcome, but little work has been done on this conjecture.

There has been some research on, and at least one implementation of, methods for quantifying the model risk due to employing input distributions that are estimated or "fit" to real-world data; see, for instance, Song, Nelson and Pegden (2014). Even in this narrow domain there are still basic unanswered questions, including how to interpret simulation optimization results in the presence of input uncertainty. The broader quantification of overall simulation model risk remains an open problem.

Model risk is unavoidable, even with best practices; but quantifying it allows decision makers to hedge against it, which is essential in business and management. Unfortunately, modelling related failures, such as the 2008 financial crisis, have cast suspicion on all model-based decisions. A national research agenda that emphasizes quantifying model risk as well as traditional model development and solution would benefit researchers and society as a whole.

### 2.2 Social Modeling (Macal)

Social modeling has advanced steadily since the works by Schelling (1971), Axelrod (1984), Epstein and Axtell (1996), and others. The state of the art in social modeling today consists of a variety of modeling techniques applied to modeling social interactions, networks and organizations. For example, large-scale dynamic agent-based models consist of thousands or even millions of agents who dynamically interact with other agents and their environment in complex ways (Macal and North 2010). Agents contend for and share resources, exchanging information, form cohesive groups, and generally engage in many forms of social contact and interactions. Such models often exhibit emergent phenomena, i.e., system behaviors that were not explicitly programmed into the models, such as the formation of groups, as a result of the repeated non-linear interactions between many agents, and are a valuable asset to understanding social processes and behaviors.

The operations research and operations management fields have traditionally emphasized modeling for normative purposes to identify optimal system configurations. This prescriptive perspective often assumes perfect rationality on the part of decision makers. Several fields, such as behavioral economics and behavioral operations management, have begun to focus on better understanding and descriptions of how decisions are actually made considering the practical limitations on time, resources and attention, as well as emotional factors. Understanding how decisions are actually made is one thing, but much work needs to be done on modeling how decisions are made within such boundedly rational frameworks (Simon 1982). One of the reasons that people come to agent-based modeling and simulation is because they would like to include truer representations of the behaviors of agents into their models. A deeper understanding of and experience with the types of models and techniques that work best for modeling various types of decisions and contexts is sorely needed.

The advent of Big Data also provides opportunities to advance social modeling. Real-time data streams coming from a variety of sources including cash register transactions, ubiquitously-placed sensors, and social media, to name a few, provide unprecedented access to data. The issue is what to do with it. It might be possible to extract social behaviors and even behavioral models directly from social media data. Kosinaki et al. (2013) demonstrate how behavioral attributes (potentially akin to market segmentation and an antecedent to developing behavioral models) can be identified from digital records. The inclusion of real-time data for updating agent (i.e. people, vehicles, etc.) states and identifying behaviors and blending that information with within forecasts is another promising area (Bengtsson et al. 2011). Ultimately, there appears to be a natural motivation to model and simulate all of society, which would have a variety of beneficial applications and uses.

A national research agenda could help social modeling first-and-foremost by creating a forum in which the key research problems to advance the field could be articulated and discussed. Collective agreement on what the most important problems are to solve in social modeling that would best advance the use of simulation to serve society's needs would be highly beneficial. For example, social processes play heavily into some of the great problems faced by society. What advances in social modeling would best advance our understanding of and help us formulate possible solutions to the problems of global climate change, water and energy security, and impending social conflict? Such a consensus would be the basis for research projects in academia as well as industry and be a basis for developing the interdisciplinary educational curricula that effective social modeling and simulation requires.

## 3 COMPUTATIONAL CHALLENGES

Computational challenges have been a main focus point of the Winter Simulation Conference. The topics highlighted here are neither complete nor exclusive, but show three highlights of research on international interest that may be also candidates for a National Research Agenda.

### 3.1 Cloud Computing (Balci)

*Cloud Computing* is a style of computing in which dynamically scalable and often virtualized resources are provided as a service over a network, e.g., Internet, virtual private network, wireless network, and Secret Internet Protocol Router Network (SIPRNET). Many virtualization technologies make up the underpinnings of cloud computing including: application virtualization, application server virtualization, desktop virtualization, network virtualization, server virtualization, operating system virtualization, service virtualization, and storage virtualization. The term “cloud” is used as a metaphor for “network”.

Software paradigm started shifting in about 1999 from *Software as a Product* (SaaP) to *Software as a Service* (SaaS). Since then, we have seen the emergence of many cloud software development platforms and frameworks including the following (Schutt and Balci 2015):

1. Java platform, Enterprise Edition (Java EE)
2. Microsoft platform, .NET Framework
3. Ruby on Rails Framework
4. Zend Framework (PHP)
5. Node.js Platform (JavaScript)
6. Python Framework

*Cloud software* is the kind of software that runs on a server computer under the control of an *application server software* (e.g., GlassFish, WildFly, WebSphere, WebLogic) and used by a user over a network (cloud) typically by using a web browser.

The U.S. Government is the largest sponsor and consumer of Modeling and Simulation (M&S) applications in the world. Millions of dollars are spent annually for building M&S applications under the SaaP paradigm for use by a number of people at a particular physical location. The U.S. Department of Defense (DoD) provides repositories of earlier developed M&S applications; however, reuse of these M&S applications or their components is prohibited because of different programming languages, operating systems, and computer hardware used for their development.

We definitely need a national research agenda to bring M&S to the cloud, start developing M&S applications under the SaaS paradigm, and enable geographically dispersed people to use the M&S applications over the cloud. We need to build on top of existing cloud computing and cloud software development technologies so that an M&S application can be developed in the cloud and can be provided as a service to the user over the cloud. For example, the U.S. Department of Homeland Security's Federal Emergency Management Agency (FEMA) can sponsor the development of an M&S application in the cloud for the purpose of training first responders, emergency managers, and citizens in the whole country. People can connect to FEMA’s M&S training application in the cloud using a web browser and be trained about what to do in case of a natural or man-made disaster.

Cloud computing is a technology for delivering IT services to the users over the cloud (network). A national research agenda should be created to conduct research by taking advantage of the existing cloud computing and cloud software development technologies to invent new methodologies, platforms, frameworks, and programming languages for the purpose of bringing M&S to the cloud and providing it as a service over the cloud. M&S development should be shifted from the SaaP to SaaS paradigm. That paradigm shift took place about 15 years ago. The M&S community must catch up with the software engineering community in shifting the paradigm.

Bringing M&S to the cloud and providing it as a service does not create a security problem for DoD since SIPRNET can be used as the network (cloud).

### 3.2 Parallel Distributed Simulation (Fujimoto)

Parallel and distributed simulation (PADS) is concerned with distributing the execution of simulation programs across multiple processors. The field emerged in the 1970's and 1980's independently from the high performance computing community who were concerned with speeding up program execution and the defense community who were concerned with simulation interoperability and model reuse. The field has grown and flourished since that time and remains an active area of research to this day. A review of the field is presented in (Fujimoto 2015).

PADS technologies occupy the "middle" of the software stack. As such, it provides services to applications residing above it in the stack, and utilizes services derived from hardware architectures and system software from below. From this perspective new research challenges can be viewed as being derived from the requirements and constraints of emerging modeling and simulation applications on the one hand, and opportunities stemming from innovations in hardware and software systems on the other. Each of these is briefly discussed next.

Hardware and system software technologies have been undergoing revolutionary changes in recent years. These changes offer new challenges and opportunities for PADS research to have increased impact:

1. *Large-scale simulations on massively parallel computing platforms*. Hardware performance improvements over the last decade have arisen almost entirely from increased parallelism rather than clock speed improvements. This has resulted in the creation of massively parallel supercomputers containing unprecedented numbers of processors or cores. Effective exploitation of platforms containing millions of cores for large-scale simulation applications remains a major challenge in the PADS research community, e.g., see (Barnes, Carothers et al. 2013). Modeling realistic large-scale networks that arise in many applications, e.g., so-called scale-free networks represents another area presenting major challenges (Pienta and Fujimoto 2013).
2. *Exploitation of heterogeneous machine architectures using Graphics Processing Units (GPUs)*. GPUs are becoming common in platforms ranging from large-scale supercomputers to clusters, desktop machines, and even mobile devices. A growing body of research has been exploring exploitation of these devices for parallel discrete event simulation applications. If successful, research in this area may enable PADS research to achieve new levels of performance for certain classes of data-parallel simulation problems.
3. *Effective exploitation of cloud computing platforms*. Cloud computing offers the ability to make PADS technologies broadly accessible to users without incurring the expense of purchasing and operating high performance computing platforms, thereby addressing a long standing issue that has prevented widespread adoption of PADS technology in the past. Existing cloud platforms present new challenges, however, due to the shared nature of the computing platform and emphasis on high bandwidth communication rather than low latency. Moreover, the difficulty to develop parallel simulation codes remains a significant impediment to widespread adoption. Domain-specific programming languages designed for efficient parallel execution may help to address this issue.

At the same time, new challenges are being driven by M&S applications. For example, there is increasing concern regarding the sustainable growth and management of modern cities both in "normal" operations and in the presence of extreme events such as natural or human-made disasters. Further, cities are undergoing a revolution with the emergence of many revolutionary technologies such as smart cars and automated vehicles, electrification of the vehicle fleet, unmanned aerial vehicles, emerging renewable energy sources, smart power grids and smart homes, to mention a few. These M&S applications impose requirements and constraints on PADS technologies. Three challenges in this area include:

1. *Rapid composition of separately developed simulation models*. It is widely recognized that understanding the growth and operations of modern cities requires an understanding of the system as a whole rather than just its components. Deep understandings of the interaction among infrastructures such as transportation, communications, water, and energy, as well as understandings of the interaction of social processes and policies on infrastructure development and use are essential. Modeling such systems-of-systems suggests an approach integrating simulation models of the component infrastructures and processes. While much progress has been made, composing separately developed simulations developed for different purposes remains a time consuming task, and may not even be possible. Techniques and tools to automate this process while ensuring the resulting models are valid require much further development.
2. *Online decision-making using real-time distributed simulation*. Increasingly the operations of cities are continually being optimized and improved through a cycle that involves data collection, prediction, and action in real time (Darema 2004). The emergence of ubiquitous computing, wireless sensor networks, and vast amounts of data enable simulations to be embedded into operational environments at unprecedented scales. Distributed simulation can play a large role in the online management and optimization of operational systems in areas such as transportation, energy, and law enforcement, however much additional research is required to explore these areas.
3. *Energy and power efficient parallel and distributed simulation*. Embedded simulation applications such as those described above call for careful consideration of power and energy consumption. Energy consumption affects battery life in mobile computing platforms and power is a major expense in modern data centers. Yet power and energy consumption has received very little attention in parallel and distributed simulation to date. Little is known concerning the power and energy characteristics of parallel and distributed simulation algorithms, nor how to effectively manage these aspects of the program's execution.

It is clear research in the above areas will have much broader applicability beyond urban infrastructures, and much work is attacking the problems cited above. However, addressing these issues as a whole rather than in a silo'd approach enables synergies to become apparent and exploited in a way that would not be possible when addressing each of these technologies in isolation.

Support for Fujimoto's research has been provided by the National Science Foundation under Grant 1441208 and the Air Force Office of Scientific Research under Grant FA9550-13-1-0100.

## 4 MEDICAL SIMULATION (COMBS)

Medical Simulation is on the brink to become the most supported application domain, only being second to the defense section, and the gap is continuously shrinking. But how can we apply lessons learned beyond the borders of the application domain?

The capacity to measure one's personal physiological and social metrics, compare those metrics with the metrics of millions of other humans, personalize needed therapeutic interventions and measure the resulting changes will ultimately realize the vision of personalized medicine—wherein patients and their providers will be able to detect disease at an earlier age; provide optimal therapy based on the characteristics of each individual and reduce adverse responses to therapy; where pharmaceutical companies can improve the process of drug discovery and clinical trials; and where the healthcare industry's emphasis truly shifts from reaction to disease to prevention of disease and promotion of wellness. Implicit in this vision is the integration of a sustained focus on improving the outcome measures of healthcare—safety, effectiveness, patient-centered, timeliness, efficiency, and equity—into clinical practice (Combs 2016, Institute of Medicine 2001).

Having the goal of improved outcomes for patients in mind helps to frame the importance of the Digital Patient: it is among the most powerful tools that we can develop and deploy to improve health.

The most commonly referenced definition of the Digital Patient is that provided through the European Union's DISCIPULUS project: "a technological framework that, once fully developed, will make it possible to create a computer representation of the health status of each citizen that is descriptive, interpretive, integrative and predictive." Not explicitly stated, but implied, is that this framework will include behavioral, social, temporal and spatial dimensions in addition to the biological in the many multi-scale models that will become its constituent components (Combs, Barham,,and Sloot 2016; Díaz-Zuccarini, Alimohammadi, and Pichardo-Almarza 2016; Pruett and Hester 2016).

Constructing the Digital Patient requires making health information linkable and computable and that requires standardization at several levels (Nickerson et al. 2016; Pruett and Hester 2016). This is illustrated in Figure 2.

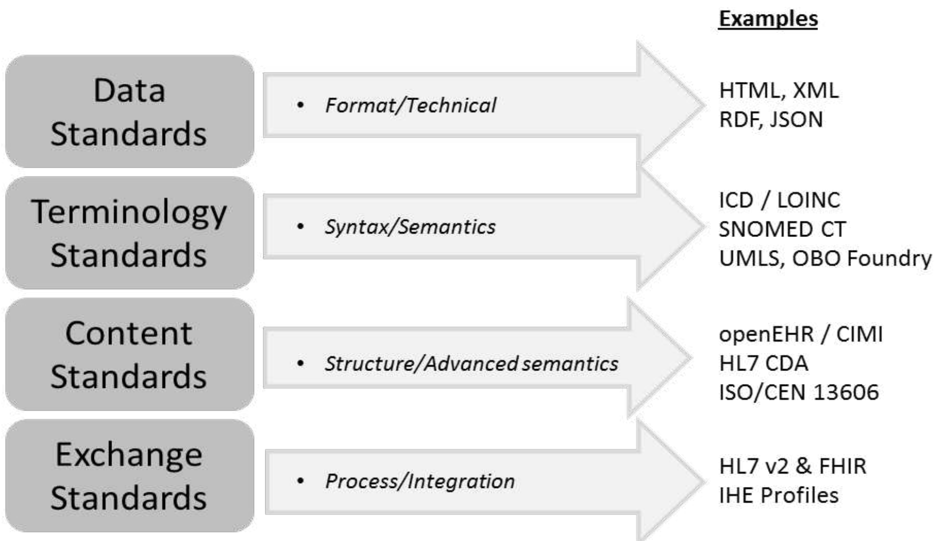


Figure 2: Different layers of standardization for health information

Realizing the potential of the Digital Patient is going to be difficult. The Digital Patient research agenda requires the establishment of an enduring, voluntary collaborative mechanism, much like the W3 Consortium governing the web, that involves an academically broad, international cadre of researchers, patients and clinicians capable, over time, of addressing fundamental challenges: taxonomic clarity, protection of privacy, integration of data and models with differing temporal and spatial characteristics, standards, and a process for accrediting the validity and reliability of the constituent models of the Digital Patient.

## 5 SYSTEMS ENGINEERING

Recent publications in the model-based systems engineering domain are recommending the increased use of modeling and simulation (INCOSE 2014), and it is starting to get integrated into the body of knowledge of relevant societies (Tolk, Rabadi, and Merino 2009). But what is the state of the art, and how can a National Research Agenda help to create more synergies?

### 5.1 Engineering Modeling (Zimmerman)

In order to answer these questions, it is important to consider multiple viewpoints within the engineering community, and perhaps by extension, in all domains which have a relationship with models and/or simulations: user of models/simulations; developer of models/simulations; and steward of models/simulations. Without diminishing the importance of domain expertise, approaching the research agenda from the suggested simple viewpoints will allow the synergies to be identified without the complication of domain areas of expertise. Within these simple viewpoints, research thrusts and results will contribute to the advancement of model and simulation application, model and simulation development, as well as the upkeep of the model and simulation infrastructure necessary to improve the enterprises enabled by models and simulations.

Any number of definitions of the word model informally suggests that it is a representation of something in reality. With that definition, it is easy to understand that engineers use models all the time – whether they are physical-scale models for use in wind tunnels or tow tanks, mathematical models that might encapsulate speed of a vehicle through a medium, data models which might describe the dimensionality of an object, and process models that might depict how a person uses a tool. (For completeness, it is also important to consider hybrids of the last three types of models.) We will concentrate our discussion on models which can be combined with current, and assumed future, computational capabilities. As computational capabilities are combined with models, and as the quantity and availability of engineering data from simulations increases, the ability to make objective decisions from the data requires new "stuff" – for example, methods for creating new models, methods for scoping the trust in the simulation (model executed over time) output, methods for making models accessible, and methods for assisting the decision makers make sense of the information. Additionally, as engineering simplifies its classification of models (data, algorithms, processes), the combination of model types with today's computational capability can add objectivity, consistency and cohesion across the multiple engineering activities in program development.

Several items stand out as being critical for the model developer. A design-related simulation environment may be very large, comprising of many codes running in series, parallel, or both, requiring anywhere from several seconds, to several hours for a single trial run. This may not be a practical or even feasible option when thousands of runs are required for an operational solution. The ability to iterate the development and test of surrogate models is therefore a key area in an evolving research agenda (Ender et al. 2010). Methods for surrogating are a second critical item for the developer. In theory, a surrogate model may be regressed around data collected from a large number of runs with random selection of values within the bounds of input variables. However, for a very complex system model requiring many time consuming computer codes to run, a structured method for data sampling with the minimum number of simulation runs is needed, such as Designs of Experiments to draw meaningful conclusions from that data set. Methods for transition from surrogate to physics-based models are critical. We would like to keep surrogates as part of the framework as long as possible, so we can maintain as much design freedom as possible with rapid new design options (e.g. tradespace exploration). However at some point we need to know the most efficient point in time to switch back to the higher fidelity models and simulations for that "deeper dive".

Understanding those questions implies detailed understanding of the models. As the employment of models increases, more will be demanded of the scope of the model coverage as well. Not all phenomenology can be modeled today; but not all un-modeled phenomenology is understood. Research into application of engineering methods using digital artifacts (e.g. digital system model, digital thread and digital twin application within the Department of Defense) to problems within program development will improve the resultant systems, as well as provide areas where additional research and tool application is necessary.

There is continued, and some would say increased emphasis in understanding the risk associated with any program development. Whether you are a developer, or a user, being able to quantify or at a minimum, bound the risk associated with the model and model application is critical to establishing the trust in the outcome of the simulation results. Trust in a model begins with its construction. Research into establishing the validity of the model as the model is built, rather than afterwards, is one area which would benefit the engineering community; and the more it is automatic, the better. For areas such as surrogate modeling, it is imperative that the regressions we create are worthy of our trust. There are multiple methods for validating surrogate models, some requiring more in-depth knowledge about statistics than others, and some are only applicable to certain types of surrogate models (primarily because they invalidate specific a priori assumptions the method makes). We are generally limited in the amount of data available or that can be generated, for this reason, the confidence and level of effort must be balanced. We must build trust in application of multiple models into increasingly complex problem as well. Application of validation and verification procedures may help, but in the case of application to new areas, the answer to the question of is it appropriate, is not a yes or no answer.

The characteristics of tools for model development and usage are critical, such as ease of use, and portability of artifacts to integration frameworks. These tools may be in the form of commercial software, or built using open source modeling languages such as *R* and *Python* and their associated libraries. Surrogate models, described above, may allow for quick calculation of responses, and must be accompanied by knowledge about the model itself to bind the validity of the results. Any use of models must support visualization of results, which is a broad need when exploiting models to explore the design space, conduct trade studies, or conduct a trend analysis. Challenges remain in presenting the large amount of information created by the increased use of models in ways appropriate to the receiving audience, and in many cases, decision makers at all levels of an engineering endeavor.

Between the developer, user and the steward viewpoints, a major need is how to make models (old or new) visible, and how to assess their applicability. Many repositories exist, more are planned, but none seem to have the staying power to answer the challenge. It must be more than the repository mechanism; it must be more challenging than metadata; it must be more complex than culture; it must be more involved than directives or policies. What is it that will allow the engineers to identify models which have been developed? What is it that will identify to model developers where gaps in models exist? What is it that will convey model employment constraints? How should a repository be structured to support engineering use in addition to ease of access? What is needed to identify different types of models, and what is necessary to use those models?

## 5.2 System of Systems Engineering (Tolk)

In the recent months, Rainey and Tolk (2015) compiled a handbook on *Modeling and Simulation Support for System of Systems Engineering Applications*. While this field has been described in many different ways, there is consensus that the focus should be on integration and coordination of multiple complex systems to provide better performance and increase functionality towards levels that are out of reach of the individual systems. The articles collected in the handbook clearly show the usefulness of agent-based approaches to better understand system of systems on the management as well as on the technical level. Principally, simulation approaches are shown to be trusted tools to understand, communicate, and manage the complexity better than with pure traditional systems engineering approaches.

Since the recent similar approach to compile the core contributions to the body of knowledge of this field by Jamshidi (2009) the advance of modeling and simulation support has been significant. Nonetheless, Rainey and Tolk (2015) observe several gaps that need to be closed by following a research agenda proposed in the last chapter of the handbook. These topics are of general interest and definitely worthy to be considered for a national research agenda as well, as various topics of national interest are addressed. The following seven topics are identified.

1. *Taxonomy:* A literature research immediately shows that the community is not speaking a common language. Mapping results to a common taxonomy will support a better understanding of the common concepts.
2. *Theoretic Foundations:* Capturing the ideas in unambiguous and rigorous formal methods is necessary to move from multidisciplinary approaches towards interdisciplinary approaches,

and ultimately to real transdisciplinary research. The field of cybernetics shows potential to be a common denominator.

3. *Organizational and Human Factors Engineering:* The human limit to handling complexity and the organizational constraints for systems with operational and managerial independence continue to be insufficiently solved challenges.
4. *Emergence:* Using sophisticated system of systems models to drive agent-based simulations to gain a better understanding is needed. We cannot afford to recognize emergence in our systems once they are in operational use, see, e.g., at possible effects for Ballistic Missile Defense given by Garrett et al. (2011).
5. *Cybersecurity.* Another topic that evolved significantly over the last years is security. The operational and managerial independence creates a significant challenge for secure solutions. M&S methods can support procurement, testing, and training on multiple levels. Static solutions and information assurance are necessary, but no longer sufficient.
6. *Model-based System of Systems Engineering.* The advantages of model-based systems engineering are well recognized by the traditional systems engineering community. Common models and repositories increased the productivity and reliability of systems engineering. These ideas, methods, and supporting tools need to be adapted and evolved.
7. *Academic and Professional Education.* Although the topic gained significant academic attention over the last years, the need for professional education on all professional levels has merely been recognized. What exactly needs to be included in curricula and continuous education lessons is open for discussion and needs to be captured as the research agenda progresses.

This list is neither complete nor exclusive. It is meant to raise awareness and hopefully contributions in the form of recommendations, but also in the form of additional research topics of general interest. One topic of interest to the Winter Simulation Conference community may be hybrid simulation ideas and how they can support System of Systems Engineering better (Chahal, Eldabi, and Young 2013).

## 6 SUMMARY

The discussions presented in the various contributions show that M&S has reached a maturity level that requires orchestrating activities on the national level. Some overarching questions that are addressed deal with central questions that surface in all domains. While some domain-specific solutions are identified, the following insights, methods, and solutions need to be generalized where possible, preferably using a common, domain-independent language to do so, for example:

- *Validation and Verification:* Can we identify common ontological and epistemological foundations for simulation applications that help us to ensure that our models are conceptually aligned with accepted theories and that our implementations are resulting in valid computational representations thereof.
- *Reusability and Composability:* The continuous advance of computer engineering methods allows to use more and more computational resources in support of parallel and distributed computation, cloud computing, the "Internet of Things," and other relevant topics. New insights in "Big Data" and "Deep Learning" may revolutionize the way we conduct M&S support (Tolk 2015). However, in order to ensure that we only compose together what fits together, more fundamental work is needed.
- *Credibility and Trustworthiness:* Whether we use simulations to provide decision support to managers, or if we use them to train surgeons and nurses, we need to find a better way to prove credibility and trustworthiness based on scientific methods.

- *Complexity and Uncertainty:* There are significant human limits to handling complexity. This is true for individuals as well as for teams. Approaches like controlled reductionism have been proven to be insufficient for addressing systemic challenges of complex systems. Using M&S to support the management of complexity and uncertainty and to educate managers in the use of this toolbox is another topic of domain independent interest.
- *Defining the Discipline:* There have been several approaches to cataloging the methods and application examples of M&S as well as to defining a set of controlled vocabularies. Although the need for establishing a body of knowledge was presented more than a decade ago (Birta 2003; Ören 2005), we still don't have a common approach. As long as M&S remains a domain-specific tool, the idea of true convergence of technology will not be possible.

The contributions to this position paper have shown that a national effort towards a research agenda can be helpful, but actually a broader approach is ultimately needed. Without the support of the international professional societies, such as represented by the organizers and sponsors of the annual Winter Simulation Conference, such an effort would fall too short. A more inclusive approach of the international community may be needed.

The principle way forward is depicted by the observations on multi-, inter-, and transdisciplinarity in (Stock and Burton 2011). In multidisciplinary approaches, experts from various disciplines are working together on a common question or topic of interest. Each discipline remains unchanged but simply contributes its knowledge, methods, and expertise. When common tools are developed and the participating disciplines start to link to each other instead of juxtaposing, the effort becomes interdisciplinary. Permanent bridges between the disciplines are established. Finally, when the participating disciplines are systematically integrated to create new knowledge components in transcending and transgressing form, a new transdisciplinary effort emerges. The following figure 3 shows these steps.

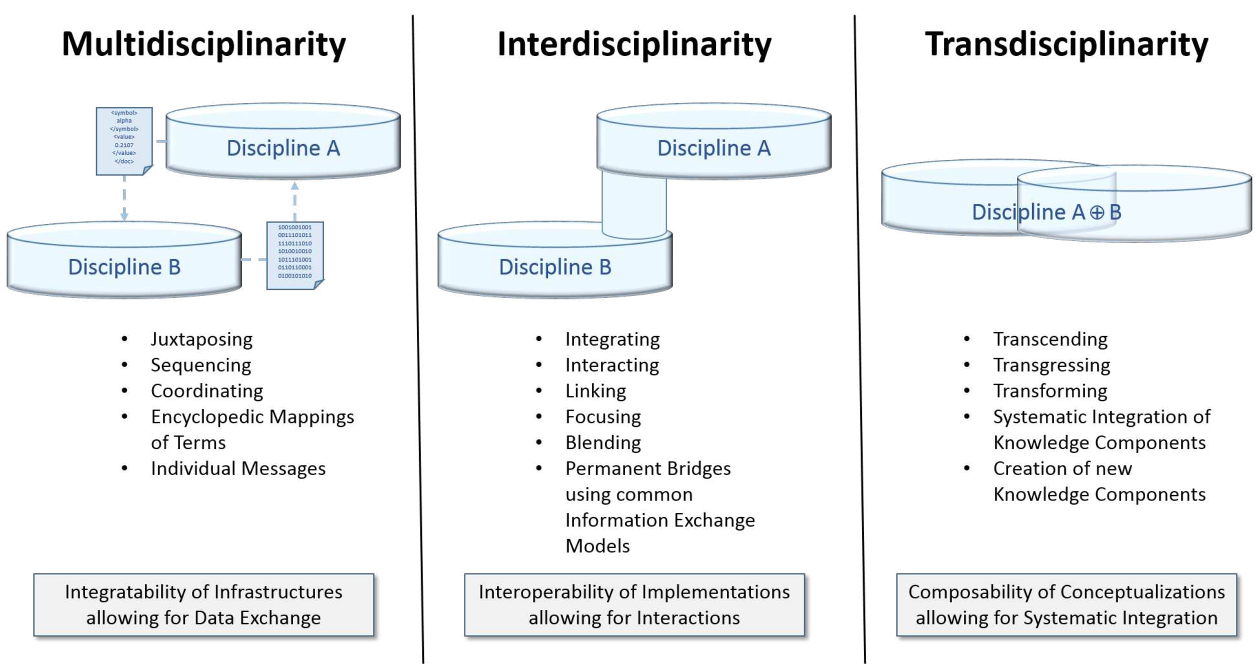


Figure 3: Multidisciplinarity, Interdisciplinarity, and Transdisciplinarity (Tolk 2016)

A national research agenda may spawn to M&S communities to intensify their efforts to continue to converge the contributing fields towards a real transdisciplinary effort that culminates in truly establishing M&S as a discipline. The contributions to this position papers are examples of the diversity of challenges and help to better understand why the convergence of M&S support – research insights, engineering tools and methods, and reuse of solutions – is feasible and applicable, but requires guidance, governance and orchestration.

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