Chapter 2
Modeling and Simulation (M&S) Technology Landscape

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Abstract A review of current investment levels in M&S research, development and application is provided, and a subjective assessment of the "leading" organizations across various applications of M&S is suggested. In addition, a number of challenge problems in M&S are identified. Our objective is to provide a starting point for organizations in their formulation of investment and technology strategies for M&S.

Keywords Analysis · Aviation · Defense · Experimentation · Healthcare · Immersion · Live-virtual-constructive · Manufacturing · Research and development · Systems design · Technology landscape · Training

2.1 Introduction

As the Table of Contents for this book suggests, Modeling and Simulation (M&S) is essentially ubiquitous across the scientific and engineering disciplines. As such, holistic, comprehensive treatments of the subject are elusive. In this chapter, we consider the technology investment "landscape" for M&S. Based on publicly available information, we characterize the interest in, and reliance on, M&S—as

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measured in terms of investment—across various domains of application, across industries, countries, and so forth. Our treatment is necessarily abbreviated and approximate, and superficial in many aspects. Certainly, more extensive treatments of this subject are warranted as the "profession" of modeling and simulation emerges. Nonetheless the cursory examination here may provide a useful starting point for business leaders and/or governmental organizations in their formulation of technology investment and research strategies.

2.2 The Global M&S Landscape

Modeling and simulation pervades science and engineering, with application in systems design and analysis, training, experimentation, mission rehearsal, test and evaluation, education and entertainment. It has been suggested (Glotzer et al. 2009) that:

> Today we are at a 'tipping point' in computer simulation for engineering and science. Computer simulation is more pervasive today – and having more impact – than at any other time in human history. No field of science or engineering exists that has not been advanced by, and in some cases transformed by, computer simulation. Simulation has today reached a level of predictive capability that it now firmly complements the traditional pillars of theory and experimentation/observation. Many critical technologies are on the horizon that cannot be understood, developed, or utilized without simulation.

Despite, or perhaps because of, this ubiquity, global investment levels in M&S are difficult to quantify with accuracy. In most circumstances, we can only measure M&S investments indirectly as a fraction of the total government, industrial, and academic investments across the scientific and engineering disciplines. In some areas, though, distinct M&S marketplaces exist, most notably those involving training simulations/simulators and Product Life-Cycle Management (PLM) software (a cornerstone of the manufacturing industry). Rigorous market analysis data is available in a few of the domains associated with these technologies, including:

- Defense training and simulation (Frost and Sullivan 2014; Visiongain 2015)
- Civil naviatio training and simulation (TechNavio Infiniti Research Ltd 2014)
- Manufacturing (CIMdata 2014)
- Healthcare (Marketsandmarkets 2014; Meticulous Research 2014)
- Emergency Management (Marketsandmarkets 2013).

Although these applications constitute a small fraction of the total M&S landscape, collectively they represent an estimated global annual market exceeding $18B USD. The countries with the highest investment levels in training simulation and simulators include: United States, Russia, China, India, and United Kingdom. The heaviest investors in PLM software are: France, United States, and Germany. Asia-Pacific and Latin America are expected to have the highest growth in medical simulation, driven by: India, China, South Korea, Singapore, Brazil, and Mexico.

An important subset of total spending is investments relating to research and development (R&D). Within the government sector, M&S R&D investments are typically embedded within the enterprise Science and Technology (S&T) budget, or as part of the Research, Development, Testing and Experimentation (RDT&E) budget for new/developing systems. Again, direct measures are elusive, but within the U.S. alone, annual R&D spending easily exceeds $100B USD (Valvida and Clark 2015). An informal scan of the programs across the Department of Defense, Department of Energy, National Science Foundation, National Air and Space Administration, National Institute of Standards and Technology, National Institutes of Health, National Labs, and Federally Funded Research and Development Centers (FFRDCs) suggests that tens of billions (USD) are oriented toward M&S-related topics annually. Global expenditures may eclipse that value by an order of magnitude.

With respect to investments by industry, in-depth market surveys for global industrial R&D funding are available. A 2016 assessment suggests that total global R&D investments approach $2T USD (Industrial Research Institute 2016). Asian countries (including China, Japan, India, and South Korea) account for more than 40% of the total investments; North America represents 30%, Europe 20%, and the rest of the world (Russia, Africa, South America, and the Middle East countries) account for 10%. Again, we can only estimate M&S as a fraction of this total R&D spending. However, the 2016 study cited above specifically identifies M&S as a critical R&D technology.

Given the value and volume of M&S workloads within scientific computing, another indirect measurement for M&S R&D investment may be the Top500 list of supercomputing sites. For 2016, countries represented in the top 25 are: China, U.S., Japan, Switzerland, Germany, Italy, France, and Saudi Arabia (Top500.org 2016).

From the data in these formal market studies, in combination with less formal assessments of the scientific literature, and the activities of scientific and professional societies, we derive a partial (and largely subjective) view of international leadership in M&S, summarized in Table 2.1. Here, "leadership" is simply an aggregated function of investment levels, publication volumes, and subjective measures of influence, notoriety, and so forth. Obviously, many important entries may be missing from this data. The entries in Table 2.1 merely suggest a starting point for any rigorous analysis relating to M&S technology investment and research strategies.

Table 2.1 A partial view of international leadership in M&S

Nation	Leading govt. organizations	Leading academic institutions	Industry leaders
UK	DSTL iDSC	Brunel Univ. University of Edinburgh Imperial College Loughborough University University of Southampton	Rolls-Royce QinetiQ Saker Solutions Simul8 Corp
Germany	Max Planck Inst.	University of Rostock University of Munich University of Stuttgart ASIM	Fraunhofer Inst. Siemens SAP Volkswagen
France	European Space Agency	INSEAD Ecole Normale Ecole Centrale Ecole des Mines St-Etienne Supérieure, Paris	Thales Dassault Systems Renault Airbus
Russia		Lomonosov Moscow State University	AnyLogic
China	Chinese Assoc. for Systems Simulation	China University of Science and Technology	
Canada		McGill University Carleton University University of Ottawa University of Calgary	Lumerical Bombardier Thales CAE Autodesk Research
Singapore	Defence, Science and Technology Agency	Nanyang T.U.	
Netherlands		Tilburg University TU Delft	

2.3 The U.S. M&S Landscape

As with global investment levels, quantifying U.S. investments in M&S is also difficult. The U.S. uses the North American Industry Classification System (NAICS) to classify business activity in the nation. Despite the notable efforts of groups like SimSummit (www.sim-summit.org), an international consortium of M&S entities across government, academia and industry, to facilitate the creation of a NAICS code(s) for M&S, none has yet been defined. Therefore, M&S activity must largely be measured indirectly.

A 2012 study established total U.S. expenditures on M&S at $50B USD annually, including $9B USD within the Department of Defense (DoD) (Old Dominion University 2012). States with significant activity in M&S, including dedicated research centers, include: Virginia, Florida, Arizona, California, and Alabama. While direct measures of M&S R&D activity are unavailable for this analysis, the total number of articles associated with the keywords "modeling" or "simulation" available within the major digital libraries (ACM, IEEE Xplore, etc.) is increasing. The number of venues for research publication (conferences, workshops, journals) also seems to be increasing. And the number of Universities granting graduate degrees in M&S continues to rise.

M&S is a topic of interest at the highest levels of the U.S. government. In June 2007, the U.S. House of Representatives approved House Resolution 487, which identifies M&S as a National Critical Technology. This resolution was developed through the M&S Congressional Caucus under the direction of Congressman J. Randy Forbes (4th District VA), and establishes the importance of M&S to the national security.

In a July 14, 2010 statement to the Subcommittee on Commerce, Trade and Consumer Protection of the Committee on Energy and Commerce, U.S. House of Representatives, Aneesh Chopra, the Chief Technology Officer and Associate Director of the Office of Science and Technology Policy, Executive Office of the President, asserted that M&S can significantly reduce the need for physical prototypes in the manufacturing sector of the U.S. economy. This, he said, would shorten product development time, reduce costs, and improve quality. Chopra believes that M&S is capable of providing the country with a crucial manufacturing edge that will lead its manufacturing renaissance (Old Dominion University 2012).

In fall 2011, the National Modeling and Simulation Coalition (NMSC) was formed (www.modsimcoalition.org). 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 national investments in M&S.

2.4 Some "Good Challenges" in M&S

Over the past decade and a half there has been significant energy in the identification and description of "Grand Challenges" for M&S (Taylor et al. 2013; Fujimoto et al. 2017). The community has done a great service in collectively generating and vetting a wide range of thoughtful and impactful fundamental research challenges. When confronted with a Grand Challenge, you generally know where to begin to look for the funding and intellectual capacity necessary to attack it, e.g., NSF, DARPA, major research institutions, etc. But what about the "lesser" challenges? The semi-formal market assessment described above was undertaken, in part, to support the development of a research strategy with a distinctly "applied" focus. We include some of those challenge areas here—which we'll call "Good Challenges"—along with their alignment to some of our identified market leaders.

We consider the application of M&S in three principal areas:

- Systems design and analysis
- Training, experimentation, and mission rehearsal
- Testing and integration.

Collectively, these areas present an interesting spectrum of technical challenges for M&S including: execution mode (standalone, human-in-the-loop, hardware-in-the-loop, real time, faster-than-real time), implementation language language(s), data management approaches, statistical methods, visualization, abstraction, and fidelity, verificationand validation, and reasoning about uncertainty and risk.

For systems design and analysis, one area of focus is **the application of high performance and ubiquitous computing, multi-model integration, advanced analytics, and visualization to support strategic-level decision-making in complex environments**. Topics of interest include:

- **Simulation-based optimization**. Within the government (and also in surprisingly many industrial settings) systems design analyses often find their basis in small set of "blessed" scenarios, and involve a fairly small number of design points. An opportunity exists to help decision makers embrace optimization-based methods—particularly those where automated support is available. Such methods are essential, for example, to the engineering of agile systems.
- **Metamodeling**. Robust analysis, typically supported by long-running experiments using high-fidelity models, is an essential component of good systems design and analysis. Making the results of such studies understandable to senior strategic-level decision-makers can be a challenge. One approach, may be through the use of metamodels generated from high-fidelity models. Allowing senior decision-makers to interact in realtime with reasonably accurate metamodels (and their visual representations) may facilitate better understanding of a system and its responses.
- **Immersive visualization**. Another approach to the problem of communicating the results of complicated models to senior-level decision-makers is through visualization. Can we develop visualization techniques that "immerse" a decision maker in the model and its results? Does such immersion lead to increased understanding and better insights? What modes of interaction with the model results can we provide? What are their relative effectiveness?
- **Ensemble modeling**. It is sometimes forgotten that a model is simply an *opinion* about the way the world works. If you are making critical decisions, you probably could benefit from having more than just one opinion regarding your course of action. Budgetary pressures within the government generally result in a narrowing of the model marketplace—there is generally an appetite for singular, definitive, models of any given phenomenon. There is an opportunity to help decision makers understand the value of ensemble modeling. An extension of this concept is *generalized crowd-sourcing* (predictive markets) by which multiple opinions/agendas are synthesized.

- **Prospective analytics**. A computer cycle is a terrible thing to waste. How should an organization take advantage of its intrinsic computing capabilities to exercise models and analytics in *anticipation* of questions a customer/sponsor may ask?
- **Merging M&S and big data analytics**. A fundamental tenet of M&S is that a model must be built with a specific purpose in mind (i.e., a specific set of questions that the model is intended to answer). However, the emergence of big data analytics may offer a challenge to this old way of thinking. What if we simply set out to create "models of the world"—representing entities and relationships as we perceive the need—and use these models to generate time-series data relating to every entity represented in the model and then apply big data analytics to the output? Does this add useful flexibility to our analytic processes?
- **Quantifying uncertainty and risk**. Computing and accumulating approximate error is part and parcel of many continuous modeling techniques, but discrete event methods (to include agent-based methods) are largely silent on this. In addition, we need better ways of relating these uncertainty measure to underlying risk.

For training, experimentation and mission rehearsal, one area of focus is **the application of immersive technologies (virtual reality, augmented reality, telepresence, visualization, synthetic environments, virtual humans) LVC integration, and low-overhead, high-automation techniques to produce low-cost/high-value environments**. Topics of interest include:

- **Virtual reality**. The positive impact on immersion on the effectiveness of simulation-based training and experimentation is well known (although "how much immersion is enough?" remains an open question). The contributions of VR technology to immersion are also well-known. As the commercial VR marketplace continues to grow, the interest in applying these commercial technologies in non-gaming contexts increases.
- **Augmented reality**. A longstanding pursuit within the military simulation community is the definition and development of architectures and technologies that enable the integration of Live, Virtual and Constructive (LVC) elements within a single, concurrent event (for training, experimentation or mission rehearsal), the effective use of AR to allow Live participants to perceive events generated by Virtual and Constructive components is needed. Unlike VR technologies, however, the commercial market for AR is waning—assessed by (Gartner 2014) to be in the "trough of disillusionment".
- **Virtual humans**. Role players are a part of most medium- to large-scale training and experimentation events. However, their presence can decrease the immersive nature of the experience, and can also introduce errors. The use of *virtual humans*—computer-generated characters that use language, have appropriate gestures, show emotion, react to verbal and nonverbal stimuli—has the potential to provide a low-cost, highly effective solution to the problems associated with

Table 2.2 A partial view of leadership in M&S (by selected topic area)

Topic	Leading gov. organizations	Leading academic institutions	Industry leaders
Defense	TRADOC NAWC TSD PMTRASYS AFAMS AMSO SIMAF RAND AFRL ARL MITRE Lincoln Labs	UCF/IST NPS AFIT GMU	NTSA NDIA Aegis VT MaK Boeing Raytheon Lockheed Martin Roland and Assoc
Aviation	AFSOR JPL NASA	MIT Caltech Stanford University of Michigan Georgia Tech	Boeing Lockheed Martin L3
Networking (cyber)		Ga Tech University Illinois FIU	Cisco Riverbed SNT
ISR	Aerospace LLNL	AFIT Carnegie Mellon	AGI Terra Bella Black Sky Global
Experimental design	RAND AFRL ARL	Northwestern, Cornell, Georgia Tech, NCSU, NPS, Tilburg Univ	Boeing, Fraunhofer Inst, Phoenix Integration
Optimization	RAND ORNL	Northwestern Cornell Georgia Tech	Boeing Google
High performance and ubiquitous computing	ORNL, LANL, LLNL, ANL, ARL, Sandia, NASA Ames, AFRL	Caltech, MIT, University of Illinois Urbana-Champaign, University Texas, Edinburgh University Georgia Tech, Virginia Tech	IBM, Cray, Google, Amazon
Immersive technology	Training Brain Ops Center	USC/ICT USF/IST	Redfish Occulus

(continued)

Table 2.2 (continued)

Topic	Leading gov. organizations	Leading academic institutions	Industry leaders
LVC integration	PEO STRI, MITRE	UCF/IST, Nanyang Technical University	Raytheon, Aegis, VT MaK, Lockheed Martin, NTSA
Embedded systems and hardware-in-the-loop	JPL, ARL	T.U. Delft, Arizona State, Georgia Tech, Carnegie Mellon University	Siemens, Boeing, Rolls-Royce, Intel

role players (Institute for Creative Technologies 2017). In addition, the use of such characters can significantly extend the range and scope of a given training or experimentation event.

- **Low-overhead event support**. In addition to the overhead associated with role players, most training and experimentation events have considerable overhead in "technical support". The provision for such technical support is a major impediment to the U.S. DoD's (among other major institutions) ability to fully realize its vision for Home Station Training (Perkins 2012).

For integration and testing, one area of focus is **the development and application of high assurance environments for system evaluation that support moving from a paradigm of "test-based confidence" to "simulation-based confidence"**. Topics of interest include:

- **Large-scale emulation**. Many cyber network effects, for example, cannot be studied at small scales. Further, the network representations much be extremely high fidelity to be effective.
- **Statistics of small samples**. A longstanding problem for the Test and Evaluation (T&E) communities. How can mathematics and statistics be most usefully applied in environments where the number of experimental trials is necessarily small? The integration of nonparametric statistics, applied asymptotics, etc., within our M&S toolkits is of interest.
- **High assurance synthetic environments**. Today's synthetic environments and virtual worlds, largely driven by the commercial gaming market, do not typically represent real-world physics in a manner sufficient to provide engineering-level analysis and evaluation.

As with our table above characterizing global leadership in M&S, Table 2.2, below presents a partial view of leadership in M&S across a variety of topic areas, with an obvious bias toward U.S. entities. Once again, "leadership" in this context is simply an aggregated function of investment levels, publication volumes, and subjective measures of influence, notoriety, and so forth. The entries in Table 2.2 merely suggest a starting point for any rigorous analysis relating to M&S technology investment and research strategies; many important entries may be missing from this data.

2.5 Summary

Due to its pervasiveness across the scientific and engineering disciplines, comprehensive treatments of M&S are difficult to construct. Nonetheless, organizations charged with defining research and technology investment strategies should always do so with a general sense of the research and technology investment strategies of both their competitors and partners. In this chapter, we present a necessarily approximate view of the M&S technology investment landscape. Our survey methodology is, at best, quasi-scientific. We cite formal market surveys and analysis where they exist, but note that these surveys only cover certain segments of the M&S domain space. Other aspects of our treatment are based on informal assessments of the scientific literature and the activities of professional societies, industrial consortia, and so forth. Many of the conclusions here are subjective. Despite these notable weaknesses, the information provided may prove a useful starting point for organizations conducting research and technology investment planning.

Review Questions

1. What are the estimated global investment levels in M&S and M&S-related technologies? How accurate can such estimates be?
2. Which regions spend the most on R&D?
3. What are the major sources of R&D funding by country/region?
4. What topics in M&S might we expect to see increasing investment in over the near-to-mid-term?

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