Chapter 1

Challenges of Combat Modeling and Distributed Simulation

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SIMULATION ENGINEERS AND THEIR MULTIPLE-VIEW CHALLENGES

There are many good books written on the topics of combat modeling and distributed simulation and most of them are used as references in this book, so why write another book on this topic? The reason is simple: while all other books in this domain successfully highlight special topics in detail none of them compiles the basic knowledge of all contributing fields that a simulation engineer needs to be aware of, in particular when he or she starts a job. To my knowledge, none of the existing books give the required holistic overview of combat modeling and distributed simulation needed to get a primary understanding of the challenges.

An editorial remark: in this book I will address the simulation engineer in the male form—using he or his as pronouns—without implying that female engineers are less common or qualified; I just prefer to address the engineer simply as he instead of complex he/she combinations or the impersonal it.

There are good books that focus on various topics of combat modeling, but they do not look at what modeling decisions mean for the ensuing simulation task(s). Other books introduce the engineer to the specifics, such as specific Institute of Electrical and Electronics Engineers (IEEE) standards for simulation interoperability, but they assume that no modeling needs to be done by

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the engineer doing the integration, although it will be shown in this book that understanding the underlying models is pivotal to making sure that the resulting simulation federations are valid. Other books on validation and verification do not address the combat modeling tasks or the distributed simulation task in detail, but all three topics have to go hand in hand. Finally, the operational analysis community developed many valuable insights that can be reused by a simulation engineer but the applicability of their results to support combat modeling and distributed simulation is not dealt with explicitly, as simulation is perceived as just one powerful tool within a set of alternative tools. For the simulation engineer, this knowledge will be educational when confronted with such broader views that need to be supported by work.

In addition to all these technical aspects, the simulation engineer has to understand the customer: the soldiers and decision makers in the military domain. The various terms and their semantics of language need to be understood. An understanding of how soldiers fight and conduct their operations is required in order to understand how to support their training and their real-world operations. Tactical, operational, and strategic principles must also be understood in order to model entities and their behavior and relations in the situated battlefield. These operations grow in complexity and are conducted on a global scale. The same is true for training and support of operations, and the simulation engineer is the person who needs to ensure that the right systems are interconnected providing the appropriate capabilities in an orchestrated fashion. An understanding of the problem is needed along with the conceptualizations of supporting models, the implementation details of the resulting simulation systems, and the applicable standards supporting the task of integrating the systems to support the soldiers. Applicable solutions need to be identified as well as selecting the best set for the task, composing them into a coherent solution, and orchestrating their execution. All aspects will be addressed in the upcoming chapters and the state of the art and current research will be presented in the invited chapters written by internationally recognized experts of their special domains. In other words: the simulation engineer has to understand the *operational foundations* of the supported domain, the *conceptual foundations* required for the modeling, and the *technical foundations* of implementing and composing simulation systems.

The chapters of this book are oriented at education needs identified while teaching various courses on ‘Engineering Principles of Combat Modeling and Distributed Simulation’ and related topics in graduate programs and professional tutorials. They address the needs of graduate and postgraduate students in the engineering and computer science fields as well as scholars and practitioners in the field. To address the variety of challenges and recommended solutions, the book is divided in four parts: Foundations addresses the operational aspects, Combat Modeling addresses the conceptual aspects, Distributed Simulation addresses the technical aspects, and Advanced Topics.

- The *Foundations* section provides a consistent and comprehensive overview of relevant topics and recommended practices for graduate students and practitioners. It provides an initial understanding necessary to cope with challenges in the domain of combat modeling and distributed simulation.

- The *Combat Modeling* section focuses on the challenges of modeling the core processes of *move, shoot, look*, and *communicate* in the synthetic environment. The simulation engineer will learn the basics about modeling a synthetic battle sphere that is the conceptual basis for simulations. Modeling is the process of abstracting, theorizing, and capturing the resulting concepts and relations in a conceptual model on the abstraction level. This section educates the simulation engineer and provides the ability for understanding these concepts and their limitations.
- The *Distributed Simulation* section introduces the main challenges of advanced distributed simulation. Simulation is the process of specifying, implementing, and executing the models. Simulation resides on the implementation level. In particular when simulation systems are developed independently from each other, the simulation engineer has to know which of these systems can be composed and what standards are applicable. The basics of validation and verification will also be explained as well as how such systems can support the operational environment of the warfighter.
- The *Advanced Topics* section highlights new and current developments and special topic areas. Recognized experts in their domains contributed these chapters. These topics address the needs of advanced students and scholars. They can be used in advanced teaching and in-depth study of special topics, or as a source for scholarly work. I invited recognized experts of these various domains to provide their insight in these chapters.

  It should be pointed out that the chapters in Part IV of this book are written by invited *Subject Matter Experts* of the advanced topics. The views expressed in these chapters reflect the views of the authors alone, and do not necessarily reflect the views of any of their organizations. In particular they do not reflect the views of the US Government or its organizations. The views are based on education and experience of the individual experts. Neither the selection of advanced topics nor the selection within the chapters is meant to be complete or exclusive, but will give examples that can be extended.

When reading the invited expert chapters the reader will notice that there is some overlap between the chapters within Part IV as well as with the first three parts of the book. For examples, Chapters 18 and 25 look into attrition modeling that is introduced in Chapter 9, and Chapters 16 and 19 look at simulation interoperability standards that are introduced in Chapter 12. This redundancy results from the idea that the chapters in Part IV of the book were written to be assigned as independent introductions into the advanced topics and as such can stand as publications by themselves. Furthermore, the viewpoint of all contributions is slightly different, which will contribute to the diversity of the presentations and therefore to the diversity of the education of the simulation engineer. It not only reflects on the multitude of domains in this body of knowledge—the comprehensive and concise representation of concepts, terms, and activities needed that make up the professional combat modeling and distributed simulation domain representing the common understanding of relevant professionals and professional associations—it also reflects the diversity of opinions within the core domain and the contribution domains.

No other compendium addresses this broad variety of topics which are all important to a simulation engineer who has to support combat modeling and distributed simulation. It is hoped that this book will replace the collection of copies of selected book chapters and proceedings papers that I had to use in the last decade to teach. However, I am sure that I will never be able to get rid of additional material for the lectures, as the research on these related topics is rapidly evolving. Nonetheless, the core knowledge captured in this book should remain stable for some time to come.

In my lectures I observed that students sometimes gets lost after the first couple of sessions as so many different aspects are important that on first look do not seem to be related. What do methods of semantic web technology have to do with validation and verification? Why is the resolution of the terrain model important to kill probabilities of military systems? For new students in the domain, even the vocabulary used becomes a challenge, as many military terms are used that need to be understood.

The following sections will provide a sort of overview of the book: where to find information, why chapters are written, what is the common thread through the books, etc.

SELECTED CHALLENGES THE SIMULATION ENGINEER WILL ENCOUNTER—WHERE TO FIND WHAT IN THIS BOOK

What should the reader expect to find in the following chapters? The first three parts of the book are structured following the challenges a simulation engineer will face in the process of conducting work. They address the foundations (the basics necessary to conduct the job correctly), combat modeling (the processes of abstracting and theorizing), and distributed simulation (focusing on building federations and supporting the soldier and decision maker). The fourth part addresses topics that give a historic perspective of where we are and where we came from as a community, in-depth presentations of theory, methods, and solutions, and more.

Finally, two annexes provide starting points for simulation engineers that are looking for more information. The first annex enumerates professional organizations and societies—structured using the categories of government, industry, and academia. For each entry, a short description is given and a website address is provided where more information and contact addresses can be obtained. The second annex gives some examples of currently used simulation systems. Both lists are neither complete nor exclusive but are meant as starting points for more research.

As the author and editor of this book I obviously hope that all chapters will be helpful to the readers. For scholars, educators, and students, the following overview can serve as an introduction to the topics. For readers who use this book more as a handbook or compendium, the overview will help them find the appropriate chapters to read in detail.

Foundations

What contributes to the foundations of combat modeling and distributed simulation for simulation engineers? What needs to be addressed? Should the focus be on how to conceptualize and theorize and build a good combat model? Or should the emphasis be on software engineering and distributed systems that are necessary and essential to support the kind of worldwide simulation federations that contribute to the success stories of military simulation applications?

The approach chosen in this book is different. It focuses, in the foundations part, on methods and solutions that allow a better understanding of the challenges that the military user faces, as the problem(s) to be solved is pivotal. Without understanding the customer, neither models nor simulation can provide insight or solutions. Furthermore, the need to understand the general limits of the approach in comparison with alternatives is needed: applying combat modeling and distributed simulation for the sake of applying it because it is technically possible cannot be a driving factor to recommend or to choose a solution. Generally, recommending one particular solution although other good alternatives are available is unethical. These ideas established the foundations for this book: ethics, best practices for operational assessment, and the problem domain of military users. Figure 1.1 shows the foundations and the four contributing domains.

The Foundation part starts with Chapter 2, dealing with applicable codes of ethics developed and adopted by professional organizations. These codes provide the central guidelines for professional conduct as proposed by the IEEE, the Military Operations Research Society (MORS), and the Society for Modeling and Simulation (SCS). All applicable codes of ethics focus on the necessity to be honest about the research and its limitations. However, ethical conflicts can arise in myriad situations, in particular when engineering goals and business interests are in conflict. Furthermore, own research interests can lead to breaching professional ethics. Simulation engineers in the domain of combat modeling and distributed simulation must clearly understand that the research and solutions are applied to train soldiers and support decisions in the defense domain and therefore directly contribute to what can be a matter of life and death, not limited to the soldiers. If, for example, a flawed design occurs in the national missile defense system, hundreds or thousands of civilians can suffer the consequences of a missile attack. Bad training leads to bad decisions which lead to less protection of those that are dependent on soldiers. Combat modeling and distributed simulation is a serious business and requires highest ethical principles to be applied.

The simulation engineer must make every attempt to ensure that the best combat models and distributed simulation solutions are applied. In order to do

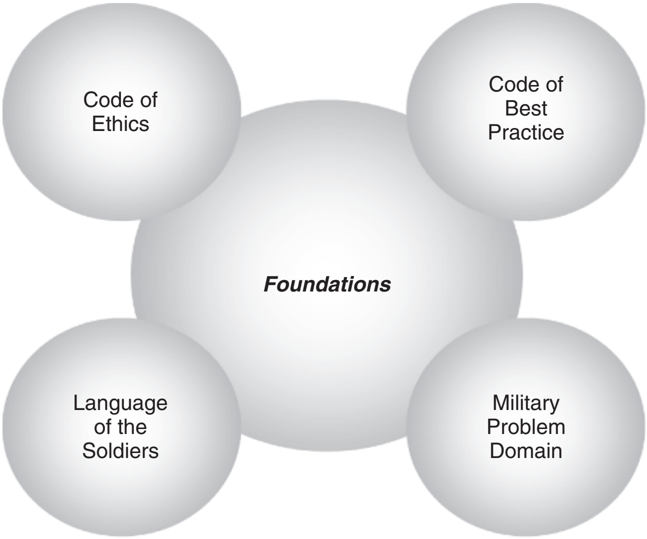

Figure 1.1 Foundations.

this, the simulation engineer needs to understand the big picture of the customer; best practices are needed to guide choices. The *NATO Code of Best Practice* (COBP) was written as a guideline for professional operational analysts on what to consider when setting up and conducting studies in general. It addresses simulation, but shows the application within an orchestrated set of tools of which simulation is just one of many. As such, the COBP addresses two important aspects. First, it shows the applicability constraints and limitations of simulations in comparison with other alternatives. Second, the best practices collected by a group of international experts in the domain of operational analysis are generally applicable, and as such applicable to studies supported by combat modeling and distributed simulation as well. How does one capture the sponsor's problem and come up with a solution strategy? How does one set up scenarios to capture applicable measures of merit of relevant human and organizational issues? How does one select the best methods and tools and obtain the necessary data? How does one reduce risks? Good practices and guidelines are provided and should be known and applied by all simulation engineers.

Chapter 3 introduces the simulation engineer to the "languages," or jargon, required to communicate in this field: those of the simulationist, the military simulationist, and the military customer. In *Terms and Application Domains*, the simulation engineer is introduced to the principles of modeling and simulation first. There are different modeling paradigms that can be used to model entities, behaviors, and relations in the battlefield. There are different domains that can be supported: the training of individual soldiers, groups of soldiers, or command posts; the evaluation of alternative courses of action in real operations; detection capability gaps in doctrine for possible future operations; procurement of new military equipment; and more. Simulationists have already developed special terms to address these concepts, but the military simulation community developed additional or alternative terms to address their areas of concern. On top of these, military language is full of terms with very special meaning the simulation engineer must know to efficiently communicate with subject matter experts. Among these are military hierarchy, the basics of weapon systems, and more in order to model required entities correctly. After studying the terms and concepts introduced in Chapter 4, the simulation engineer will be able to study papers on special topics without too many difficulties regarding the language used.

The last chapter of the first section, Chapter 5, builds a bridge between the foundational understanding and how to model the concepts. The chapter *Scenario Elements* gives an overview of the military entities, their behavior, and their relations within the situated environment. It puts the terms and concepts introduced in Chapter 4 into the context of combat modeling. The *principle of alignment and harmonization*—that is applied subsequently in the following chapters—is introduced and motivated. This principle requires the alignment and harmonization of what we model (represented concepts), the internal rules driving the behavior (decision logic), and the applied measure of merits defining the success (evaluation logic). It can be understood as follows: (1) if something is modeled, it should be used in the model; (2) if something is used, it needs to be measured and evaluated regarding how successfully the use contributed to the overall success; and (3) the overall success must be guided by the common purpose behind the simulation. The common purpose is solving the sponsor's problem by addressing the research question. If any of these aspects of this principle is violated, strange behavior and unintuitive results will result.

Equipped with the theory, the methods, and tools, the simulation engineer can now address the challenges of modeling entities to answer the needs of the sponsor.

Combat Modeling

Modeling is the purposeful abstraction and simplification of the perception of a real or imagined system with the intention to solve a sponsor's problem or to answer a research question. Combat modeling therefore purposefully abstracts and simplifies combat entities, their behaviors, activities, and interrelations to answer defense-related research questions. There cannot be a general model that answers all questions, and even if such a model could be constructed it would become more complex than the real thing, as it not only includes real systems but also imagined ones. How does one address such a challenge in a book on combat modeling and distributed simulation?

The way chosen in this book is captured in Figure 1.2. In five chapters, Chapter 6 to Chapter 10, the simulation engineer will learn how to model the core activities that can be found on every battlefield: *shooting*, *moving*, *looking*, and *communicating*. This traditional combat view is generalized into modeling intended effects of actions, movements on the battlefield including transportation

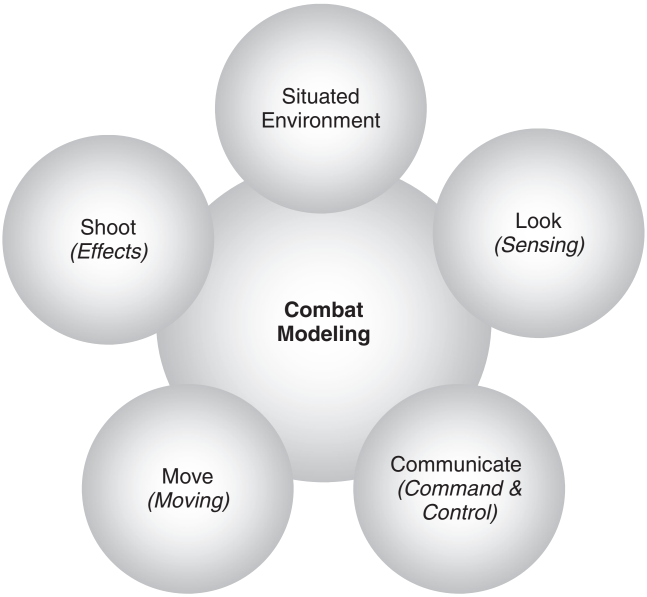

Figure 1.2 Combat modeling.

and mounted operations, modeling sensors that help the soldier to understand what is going on in proximity on the battlefield, and modeling the various aspects of command and control: generating orders and observing their execution by subordinated entities.

The part on *Combat Modeling* starts with analyzing the challenges to model the *Situated Environment.* All modeled combat entities are situated in their environment, the virtual battlefield, or the battle sphere. They perceive their environment including other entities, and map their perception to an internal representation based on its knowledge and goals. They communicate and act with other combat entities. The environment contains all objects, passive ones, like obstacles, as well as active ones. As such, modeling the environment is as important as modeling the entities and their core processes. Even more, the modeling choices for core processes are constrained by the model chosen for the environment. For example, if the environment models vegetation appropriately the influence of seasons on visibility can be evaluated: if the vegetation is leafy it may block visual contacts while other entities can be easily spotted through the branches of trees in the winter. Again, the principle of alignment of data and harmonization of processes comes into play: if something is important for the military operation, then it should be included, used, and evaluated. In particular when, in the third part of the book, several alternative models have to be combined the need for the simulation engineer to understand all these aspects and how they can be composed becomes obvious.

The first core process evaluated in more detail is *Modeling Movement.* The chapter introduces entity level models that deal with the movement of individual weapon systems as well as aggregate models that are used to model the movements of groups of systems. A tight connection with the modeling of the environment is not only obvious for land based systems, as clouds and thunderstorms can influence the flight paths of aircraft, and currents can constrain movement on and under water. The models use patches and grids; they use physical models for weapon systems and reference schemas for unit movement. The focus in this chapter lies on models used to move on land, but the ideas can be generalized for air and sea based movement as well.

The next of the core processes described is *modeling sensing*, answering the question: how does one look on the battlefield? Addressing this process increases in the light of new technological advances as well as new types of military operations that even include terms like information warfare (the fight for and with superior information), or even more important in this context, information superiority (knowing more than your adversaries). To gain and ensure situational awareness—knowing what is going on and how things unfold on the battlefield—becomes a main capability in modern warfare. Various types of sensors, such as acoustic, chemical, electromagnetic, thermal, and optical sensors, can contribute to perceiving the environment and the other entities as close to reality as possible. In real operations, military decision makers will be confronted with wrong, contradictory, and imprecise information; training situations need to prepare them realistically for this kind of challenge. Intelligence, surveillance, and reconnaissance operations contribute to similar requirements. And as before, the alignment and harmonization principle becomes pivotal: in order to sense special properties of an entity, each of these special properties needs to be modeled explicitly. If it is modeled explicitly, it needs to make a difference in the reconnaissance process. Examples are extra antennas on command and control vehicles that otherwise look like other combat vehicles. Similarly, weather influences are important as they may affect the sensors' need to be modeled in the environment. Furthermore, if a detail is important for the military decision process, it needs to be part of the perception, and hence needs to be observed by sensors, which requires that the respective things are modeled as properties of the entities.

Chapter 9 deals with the topics most traditional combat modeling books focus on, *Modeling Effects.* Effects on the battlefield are no longer limited to attrition, but modeling the outcomes of duels between weapon systems and battles between units is still a topic of major interest. After all, fighting against opposing forces is the main thing for which troops are trained and weapons are designed. On the weapon system level, direct and indirect fire are analyzed. Direct fire means that a more or less straight line between the shooter and the target describes how the bullet flies. Artillery systems and other ballistic weapons do not need to see the target and shoot at it straight. Their weapons follow a ballistic curve being described by the term indirect fire. Many models have been developed to keep up with the score, from game based point systems that count how often and where a target is hit to hit and kill probabilities that use real-world data derived from battles or from live fire ranges and exercises. Damage classes are used to find out what effect a hit has: a system can be totally destroyed or merely show any effect at all, depending on who the shooter is and who the target is. This chapter also deals with the famous Lanchester models of warfare that describe attrition of aggregated units in the form of differential equations. Other effects are only mentioned in this chapter. The reader is referred to other in-depth publications to deal with them in more detail. The chapter on modeling effects closes with an overview of Epstein's model of warfare and looks at some new approaches that take recent developments in agent directed simulation into account.

Finally, the second part of this book closes with a chapter on *Modeling of Communications, Command and Control.* It ties all the earlier chapters together as command and control is situated in the environment and commands the entities to shoot, move, observe, and communicate. Several models of command and control in military headquarters are discussed, as more and more simulation models have to come up with decisions based on available information where until recently human decision makers had to be involved. The better command and control is modeled the less military experts are needed to provide a realistic training environment. Furthermore, only when partners and opponents behave realistically can the resulting simulation systems be used in real operations to support the evaluation of alternative options. The chapter closes with some detailed observations on how messages are used in the real domain to communicate and how this can be used to model communication.

In summary, the second part on combat modeling will give the simulation engineer the necessary basic understanding of how military operations comprising moving forces, observing the battlefield, engaging the opponent, and communicating to optimize the engagement can be modeled. The simulation engineer will appreciate the principle of aligning the data and harmonizing the processes of all these models to ensure consistency and avoid wrong results and strange behavior, an exercise the simulation engineer will be able to use often when dealing with the topic of the following part of the book: composing a simulation federation out of several independently developed simulation systems.

Distributed Simulation

The third part of the book addresses the challenges of and existing methods, tools, solutions, and guidelines for composing several in general independently developed simulation systems into a federation. Providing homogeneous support of required capabilities by composing heterogeneous solutions that expose implemented functionality is conceptually demanding as well as technically sophisticated. Many of the conceptual tasks of aligning the data and harmonizing the processes can be supported by the engineering principles introduced in Part II. The focus of this part is the technical integration based on available methods and guidelines that are provided in particular for defense modeling. Many of these methods can be applied in slightly modified form for domains other than

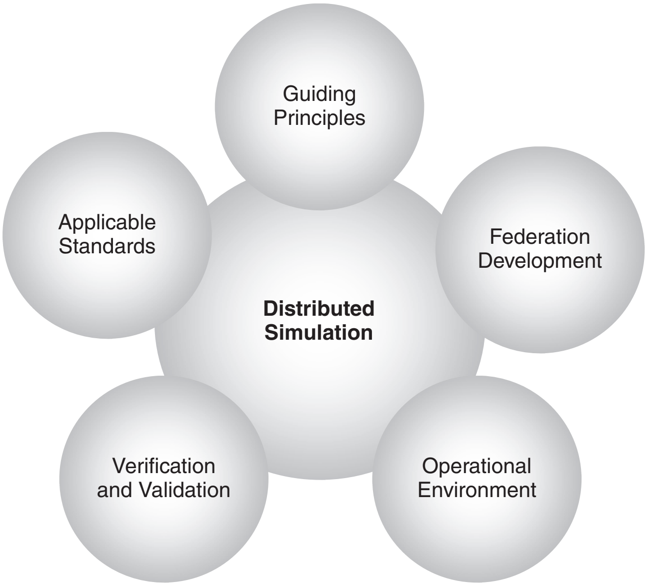

Figure 1.3 Distributed simulation.

the defense domain as well—and they will have to be applied when federations comprise tools from supporting domains, such as social science models in support of human, social, cultural, and behavioral modeling.

Part III deals with five core topics to focus on the technical foundations of combat modeling and distributed simulation, which are shown in Figure 1.3. First are the general principles of advanced distributed simulation that need to be assured in every simulation federation, no matter which simulation interoperability standard is applied or which architecture viewpoint is supported. Next are applicable standards that can support the federation development process, followed by several guidelines and best practices for the process of building a federation itself. The last two topics deal with verification and validation challenges and how to integrate simulation systems and simulation federations into the operational environment of the military user.

In Part II of this book, the conceptual foundations are laid to understand the modeling challenges of combat modeling and distributed simulation. Before diving into the technical aspects of distributed simulation, many of those aspects addressed and supported by software engineering principles, Chapter 11 on *Challenges of Distributed Simulation* puts the conceptual foundations into the context of identifying applicable simulation systems that can contribute to address the sponsor's need and evaluate the modeling question, selecting the best systems under the given constraints, composing the selected solution to provide the required capabilities as a coherent federation, and orchestrating their execution. The application of engineering principles helps avoid inconsistencies, anomalies, and unfair fight situations. Furthermore, the infrastructure that needs to be provided has to support the interoperability protocol and the information exchange model must fulfill three requirements: (1) all information exchange elements must be delivered to the correct simulation systems (effectiveness); (2) only the required information exchange elements must be delivered to the simulation systems (efficiency); and (3) the delivery must happen at the right time (correctness). The chapter addresses issues of distributed computing, looks into consistency requirements and challenges for entities, events, and states, time management, and addresses multiresolution, aggregation, and disaggregation. The chapter closes with a section on interoperability challenges and engineering methods that can be applied to support the simulation engineer in the task of selecting the best methods, tools, and solutions to conduct the job. These include general aspects on interoperability infrastructure studies conducted by experts under the lead of the Simulation Interoperability Standards Organization (SISO) as well as the Levels of Conceptual Interoperability Model (LCIM) that have been developed at the Virginia Modeling Analysis and Simulation Center (VMASC) to generally address interoperability and composability challenges in the system of systems environment as exposed in the domain of federation development.

Following this introduction and overview, Chapter 12, *Standards for Distributed Simulation*, focuses on the technical standards. Applicable guidelines, that also have been standardized, are dealt with in a later chapter in more detail. The view of this chapter is purposefully broad and not limited to the simulation interoperability standards predominantly applied in the defense domain. The vision of the SISO is to serve the global community of modeling and simulation (M&S) professionals, providing an open forum for the collegial exchange of ideas, the examination and advancement of M&S related technologies and practices, and the development of standards and other products that enable greater M&S capability, interoperability, credibility, reuse, and cost-effectiveness. Therefore, the chapter starts with an overview of past and current standardization activities. Some of these are dealt with in more detail in advanced topic chapters in Part IV of the book, such as base object models described in Chapter 19, the tactical data link simulation standards in Chapter 23, or the military scenario definition language in Chapter 24. Not all successfully applied engineering principles and resulting methods, tools, and solutions have been standardized. The Test and Training Enabling Architecture (TENA) described in Chapter 20 is an example. After this overview on SISO related activities, the chapter gives an introduction to other activities of the community—borrowing from the systems engineering community—and describes the basics and applicability in the context of combat modeling and distributed simulation of the Discrete Events Simulation Formalism (DEVS), the Unified Modeling Language (UML), the System Modeling Language (SysML), and the US Department of Defense Architecture Framework (DoDAF). DEVS and DoDAF are also topics of in-depth chapters in Part IV. The semantic web stack of supporting standards for web based distribution and alignment of interpretation of data closes the general overview. The chapter closes with describing the two IEEE Modeling and Simulation Interoperability Standards: the

IEEE 1278 Distributed Interactive Simulation (DIS), and the IEEE 1516 High Level Architecture (HLA).

Chapter 13 covers several of the methods and guidelines for *Modeling and Simulation Development and Preparation Processes.* Technical standards and solutions can address most challenges that arise from different infrastructures, networks, or communication protocols, but if the principle of aligning data and harmonizing processes is violated, they cannot help. Technical standards cannot be used to solve conceptual problems—conceptual solutions are needed instead. Supporting methods and guidelines have been developed in several professional organizations. One of the most general views is captured in a guidance document developed by the US Modeling and Simulation Coordination Office (MSCO) using modeling and simulation as a means within the problem solving process. This guideline distinguishes three use cases for M&S: (1) developing new M&S solutions; (2) adapting existing M&S solutions for new problems; and (3) constructing an M&S federation. In particular the third use case is supported in detail for the high level architecture standards by the standardized guideline for the Federation Development and Execution Process (FEDEP) and the Synthetic Environment Development and Exploitation Process (SEDEP). The generalization of these processes resulted in the most recent standards, the Distributed Simulation Engineering and Execution Process (DSEEP). All three processes—FEDEP, SEDEP, and DSEEP—are introduced and compared, as they have slightly different viewpoints on challenges to address and how to address them. The simulation engineer should know all three of them, as even if only one of them is used explicitly in support of the project, the alternative views can still be used to guide solutions based on a broader understanding of the problems. The chapter closes with a new project management method that in particular is useful in service-oriented distributed environments: the SCRUM methodology. SCRUM allows users to explicitly take the agility of the problem domain—the rapid and continuous change of operational constraints and resulting requirements—into account. In particular when new generations of distributed simulations are based on standards developed for the semantic web, SCRUM can be used to guide federation development processes in support of lifecycle use cases of federations instead of limited point solutions.

The next chapter, Chapter 14, addresses *Verification and Validation.* Ultimately, the application domains of combat modeling and distributed simulation are connected with the well-being of humans. Wrong decisions based on the application of wrong solutions or the rejection of correct advice as well as insufficient training of soldiers using insufficient training simulation systems will likely result in harm and even the loss of lives. The processes of verification and validation (V&V) should not be confused with quality control means of software engineering that address the implementation challenges. V&V mainly addresses the conceptual challenges. The chapter starts with an overview of the underlying academic groundwork showing that the objective of correct and suitable solutions may be out of reach, but that heuristics can be applied to create solutions that are at least credible. Credibility is based on the whole process integrating the various aspects. While validation ensures the accuracy of the process leading to a suitable model for the intended purpose, verification ensures the accuracy of the software engineering process and the information preserving transformation processes ensuring the use of the right scenario and the right data to complete these processes. As such, the NATO Code of Best Practice principles are utilized and the principle of aligned data and harmonized processes is supported as well, closing the circle. The following principles of V&V ensure good results: (1) V&V must be an integrated activity with model selection, development, and integration activities; (2) the intended purpose needs to be specified precisely; (3) sufficient knowledge about the system to be simulated is necessary; and (4) sufficient V&V tools and V&V experts are available. The Verification, Validation, and Accreditation (VV&A) Recommended Practice Guide (RPG) provides guidelines to support the simulation engineers to meet such requirements by defining roles, tasks, and products. Outside of the United States, the European effort Referential for Verification, Validation, and Accreditation (REVVA) is important to know.

The final chapter of Part III, Chapter 15, deals with challenges the simulation engineer has to solve when tasked with the *Integration of M&S Solutions into the Operational Environment.* The operational environment is the environment of the sponsor, which normally is the military decision maker or the soldier. The infrastructure used by soldiers to support their command and control of operations is often significantly different from the simulation infrastructure with which the simulation engineer is familiar. The chapter starts with several use cases that require the coupling of operational and simulation infrastructures, focusing on training, testing, and decision support. It describes the standards used in the operational environment, such as tactical messages and their format, the Common Operating Environment (COE), the Multilateral Interoperability Program (MIP), and the Global Information Grid (GIG). The chapter closes with current research work on frameworks that can facilitate the work of the simulation engineer. It also introduces the underlying ideas of current standardization efforts for a common language that helps to bridge the gap between different operational views within a coalition as well as between different implementation decisions in supported information infrastructures: the Coalition Battle Management Language (C-BML) that is intended to become the common unambiguous language used to command and control forces and equipment conducting military operations and to provide for situational awareness and a shared, common operational picture.

In summary, Part III of the book provides the simulation engineer with the technical foundations to construct federations and to identify the best practices and guidelines that help to ensure conceptual consistency. It helps with validation and verification methods and shows the simulation engineer how to integrate M&S and operation solutions to the benefit of the warfighter.

Advanced Topics

While the first three parts of this book are rooted in the material used to teach the engineering principles of combat modeling, Part IV on advanced topics comprises a number of invited chapters on special topics. These chapters either can be read in parallel to the first three parts of the book to provide alternative views and opinions, or they can be read as an independent part that summarizes the state of the art in the form of a compendium or handbook. For scholars and students, these chapters can become an introduction of a problem sub-domain that still exposes several gaps that are required to be closed. For faculty and teachers, the fourth part of the book can be used either to prepare a course for advanced students or in support of additional research assignments in parallel to the coursework captured in the first three parts.

Chapter 16 introduces the simulation engineer to the *History of Combat Modeling and Distributed Simulation.* In order to better understand where we are it is necessary to understand where we are coming from as a community. This chapter gives an overview of the history of combat models and simulation from board games and maneuvers to modern day worldwide distributed international training federations. It starts with early board games used to teach tactical understanding and ends with recent efforts to integrate live systems with simulators and simulation systems to provide global exercise capability. Only those who know their history are not doomed to repeat the same mistakes again, so there are many valuable lessons learned in this chapter.

Chapter 17 deals with *Serious Games, Virtual Worlds, and Interactive Digital Worlds.* The growing community of game developers does not always focus on engineering principles of combat modeling and simulation. However, modern simulation systems not only have their roots in games, today's simulation systems and computer games share technical, social, and economic domains. Common visualization tools and solutions decrease development costs and may even increase the credibility of solutions. This chapter gives an overview of commonalities, differences, and trends between combat modeling and distributed simulation and serious games and shows where mutual support of both communities is possible and desirable.

Chapter 18 provides a deeper introduction to two topics of special interest to combat modeling, namely game theoretic applications, in particular in the context of operational analysis, and Lanchestrian models of warfare. *Mathematical Applications for Combat Modeling* introduces more background and theory for Lanchester's models of warfare that are still dominating aggregated attrition models. In order to better support rational decision making, the application of game theoretic ideas can be applied. In particular when several individually developed and principally independent systems are federated into a system of systems, the optimum for the federated systems only sometimes results from individual optimal decisions within all contributing individual systems. As such, this chapter is a great enhancement to the general principles discussed in Chapter 9.

Chapter 19 addresses two standardization efforts of general interest and complements the description given in Chapter 12. This chapter on *High Level Architecture and Base Object Models* documents two success stories of the SISO. In the focus of this chapter are new standardization efforts and developments. The High Level Architecture (HLA) continues to be improved to meet the needs for distributed simulation better. Modular federation object models and better support of net-centric environments are two aspects that are currently discussed and recently integrated into the standard. In addition, new standard developments, like Base Object Models (BOM), support HLA as well as alternatives. This chapter gives a broad overview of how the standards on HLA and BOM were developed and where they are heading. It can serve as an independent introduction to the topic.

Chapter 20 deals with a very important topic that did not get enough attention in the first three parts of the book: the *Test and Training Enabling Architecture* (TENA). Developed under a joint interoperability initiative within the US Department of Defense, TENA has been designed with the goal of enabling interoperability among ranges, facilities, and simulations in a quick and cost-efficient manner, and fostering reuse of range resources and range system developments. This section will give a better overview of the TENA components and their application(s). As the application of TENA is not limited to the United States—many partner nations are using TENA and are contributing actively to its continuous improvements—and also not limited to testing—several training events were successfully supported by TENA—the simulation engineer should know philosophy, theory, methods, and solutions as discussed in this chapter.

Chapter 21 introduces the simulation engineer to *Combat Modeling using the DEVS Formalism.* Within the United States, the application of the Discrete Event Simulation (DEVS) formalism, as introduced in Chapter 12 of Part III, for combat modeling and distributed simulation was until recently nearly completely limited to academic efforts. In other nations, in particular in the Pacific domain, the use of DEVS to develop combat simulations for the armed forces is a well known procedure. Because DEVS defines system structures as well as behavior and uses atomic components to build up composites that finally represent the modeled systems, its application allows the application to combat models, as hierarchical structures and necessary capabilities for operations are well captured. The chapter describes a real-world application within the Korean armed forces.

Chapter 22 addresses a topic of growing interest, using *Geospatial Data for Combat Modeling.* Geospatial information is as important for military operations as it is for operational data. This chapter examines how to model and integrate geographic information system (GIS) data for combat modeling and prepare the distribution of data in distributed simulation environments. The operational community with command and control systems is facing similar challenges, so that common standards may be possible. The chapter introduces important standards and procedures as currently used within the GIS community and gives examples on how these approaches can be used to enrich M&S solutions.

The *Tactical Data Links* (TADL) for military command and command are standardized across NATO partners and other allies to support in particular air operations, but they are used in all services. They were addressed in Chapter 10, as they are important for modeling command and control, and in Chapter 15, as they can be used for integration purposes of M&S into the operational environment as well. This real-life command and control standard was also standardized in M&S standards to allow for their evaluation as well as their support for more realistic training. This chapter introduces the military view on TADL as well as the resulting standards and their application, as the simulation engineer must know them. Every military application that uses TADL, from air defense to missile operations, should evaluate the applicability of the ideas as captured in Chapter 23.

Chapter 24 introduces another successful standardization effort of interest to all simulation engineers, the *Military Scenario Definition Language* (MSDL). MSDL is a standard used to describe the initialization data for combat simulation systems. It allows several simulation systems to be initialized with the same consistent set of scenario data. It also provides a common language for heterogeneous authoritative data sources to provide their data to potential users. MSDL was introduced in Chapter 12 and mentioned also in Chapter 15. This invited chapter, however, gives a much more detailed technical overview of the XML schema and its use in support of scenario distribution and systems' initialization. MSDL is internationally used and supported.

Chapter 25 returns to the conceptual challenges and provides valuable information regarding various *Multi-Resolution Modeling Challenges.* Whenever models of different resolutions have to be federated, multi-resolution problems have to be solved. Several heuristics have been developed in the community to cope with the challenges. This field of research can look back to many successful and documented solutions that the simulation engineer should be aware of. Among other means, the chapter provides a tabular overview of important research results. The chapter is a very valuable in-depth add-on to the general principles introduced to the simulation engineer as an overview in Chapter 11. The examples can neither be complete nor exclusive, but they definitely are a great start for every simulation engineer to learn more.

Another problem addressed in principle several times in the first parts of the book is the fact of new operational scenarios. Today's military focus has moved away from the force-on-force battlefield of the past century and into the domain of irregular warfare and its companion, security, stability, transition and reconstruction missions. Knowing how to model moving, sensing, communicating, and shooting is still needed, but not sufficient. Chapter 26 addresses *New Challenges: Human, Social, Cultural, and Behavioral Modeling.* The success of this new type of operation depends on understanding social dynamics, tribal politics, social networks, religious influences and cultural mores. This chapter introduces the simulation engineer to this new world that is characterized by the absence of standards and established models and requires new approaches that the community so far has not yet agreed upon, and may conceptually never be able to do, as psycho-socio models do not follow a commonly accepted world view, such as physics-based attrition and movement models do.

Chapter 27 describes an approach that may help with the application of human, social, cultural, and behavioral models. It introduces *Agent-directed Simulation for Combat Modeling and Distributed Simulation.* The agent metaphor changed the way simulations are written and used in many domains, and combat modeling and distributed simulation is no exception. This chapter introduces the foundational ideas of agent-directed simulation and gives selected examples of agent applications. An agent can be understood as a software object with an attitude: while normal objects expose their methods to the user and execute the methods when invoked, an agent decides if and how the simulation engineer reacts to invocations. This makes the agent metaphor a powerful approach to represent human beings within simulations as well as to represent independent and individual systems with system of systems environment.

Another aspect that is introduced, in principle, in several places but in particular in Chapter 8 and in modeling sensing is the aspect of representing uncertain, incomplete, vague, and contradictory information. Chapter 28 introduces methods for *Uncertainty Representation and Reasoning for Combat Simulation Models.* This chapter is a little bit more challenging from the underlying mathematics but is suitable for graduate students of engineering disciplines or of computer science. It introduces Bayesian theory with Bayesian networks as well as multi-entity Bayesian networks and applies these ideas to build a vehicle identification Bayesian network. The theory is then generalized into the probabilistic argument and applicable related theories. The simulation engineer will find several useful methods and tools to better cope with uncertainty and vagueness in combat modeling and distributed simulation challenges.

Chapter 29 describes an engineering method developed at the Virginia Modeling Analysis and Simulation Center in more detail: *Model-Based Data Engineering* (MBDE). Models are individual abstractions of reality and will necessarily result in different scope, different structure, and different resolution. MBDE was developed to support developers of federations with a heuristic to identify shareable data and common concepts. In particular for scholars of data modeling theory, this chapter will be a valuable tool to identify shareable information between simulation solutions—or systems of the operational environment. If applicable data units have to be identified or a common information exchange model needs to be created from the beginning, MBDE heuristics help to avoid many common mistakes.

The multifaceted and multidisciplinary field of systems engineering and the emerging new discipline of system of systems engineering address several challenges identified for combat modeling and distributed simulation. Chapter 30 describes *Federated Simulation for System of Systems Engineering* and provides a “look over the fence” to make simulation engineers aware of engineering principles developed in these domains that can support tasks. It provides a framework to deal with the growing complexity in three steps. The first step defines system of systems engineering and provides an overview of engineering and modeling and simulation approaches prescribed for that context. The second step highlights engineering principles that are particularly relevant in a system of systems context. The final step prescribes a systems engineering methodology for federation development comparable to the approaches described in Chapter 13, but written from the systems engineering perspective. Several practical application examples are given to educate the simulation engineer on this broader and more holistic viewpoint.

Chapter 31 follows this topic by providing an introduction to *The Role of Architecture Frameworks in Simulation Models.* The simulation engineer has already been introduced to architecture frameworks in Chapter 12, but the viewpoint presented in this chapter is an extension thereof. Defense systems have to be described by means of the DoD Architecture Framework. This chapter shows possible mutual support of simulation and architecture efforts, such as enriching DoDAF artifacts to allow for executable architectures. The main focus of the chapter is showing how to extend the DoDAF to include the human view components identified in recent NATO efforts.

The final chapter of Part IV, Chapter 32, describes *Multinational Computer Assisted Exercises* from a practitioner's viewpoint. NATO is organizing multiple M&S efforts in support of training, planning, and support of operations. It established several M&S centers to enable such endeavors. This chapter will give an overview of related activities with focus on the particular challenges of multinational environments. In particular for simulation engineers that have to support multinational endeavors this chapter may be a good starting point for further research.

Annexes

Two annexes provide some start-up information for new simulation engineers in tabular form.

Annex 1 enumerates *Organizations of Interest for Professionals.* Using government, industry, and academia as categories, some selected organizations are enumerated in alphabetical order. Web resources are provided to continue the research. This list can neither be complete nor exclusive and should be extended by the simulation engineer to document personal networks.

Annex 2 gives some *Examples for Combat Models and Distributed Simulations.* This annex describes several currently used simulation solutions and gives references for additional information. Examples include Joint Semi-Automated Forces (JSAF), Joint Conflict and Tactical Simulation (JCATS), Virtual Reality Forces (VR-Forces), and others that were provided by the international community in the course of writing and editing this book.

SOME CRITICAL REMARKS

Before ending the first overview chapter of this book, some critical remarks may be in order. All references supporting the topics described so far will be given in the following chapter, but for these concluding remarks some references are needed, as the ideas are not dealt with in detail in the following chapters.

No other domain-applied M&S is as successful as the military domain. Worldwide training and testing events, multi-million dollar budgets for supporting M&S activities, and the recognition by the US Congress as a "National

Critical Technology" in its House Resolution 487 in July 2007 are just some examples that have no comparison in other domains. Not even the sky seems to be the limit, as space operations and cyber operations are already included in the military scenarios. But despite all the supporting standards and guidelines to be presented in this book we must ask the question: How good are we in combat modeling and distributed simulation really?

In their 1991 White Paper on the State of Military Combat Modeling, Davis and Blumenthal identify several problems with the use of M&S within the US Department of Defense. Actually, they made the statement that the use of combat modeling and simulations within the US DoD at this point in time was fatally flawed, so flawed that it could not be corrected by anything less than structural changes in management and concept. The lack of a vigorous military science as the foundation for combat models and their validity resulted in (1) dissonance of approaches in the community; (2) use of inadequate theories, methods, solutions, and models; and (3) ultimately chaos in combat modeling that became worse by unsolved challenges in the software engineering realm. A particular problem was that nobody was really in charge. That resulted in a multitude of not harmonized approaches resulting in incompatible solutions. Twenty years later, history is in danger of repeating itself. Strong and scientifically competent central organizations are gradually replaced with local organizations and steering committees. Whether they will succeed in the challenge of successful alignment and harmonization remains to be seen, but some critical remarks in the community already warn that we may sink back into "dark ages" (Hollenbach, 2009). With the knowledge provided by this book I hope to raise the awareness of a strong and holistic management approach to combat modeling and distributed simulation, as strong engineering principles are necessary, but not sufficient.

The second word of warning regards the technical maturity of our approaches. The methods, tools, and guidelines compiled in this book are mainly derived from physical technical models. They assume that all models are derived from the same real-world systems on the same battlefield following the same laws of physics. Discrepancies in models can be reduced by increasing the resolution and by aligning the data and harmonizing the processes to the same level of aggregation. This viewpoint is rooted in positivism as the driving philosophical foundation, as it is appropriate for the majority of physical-technical models that follow the Newtonian worldview of physics. Unfortunately, this worldview also underlies the current interoperability standards, tools, and guidelines. It would be naïve to apply standards that were developed for physical-technical models based on a common theory representing the positivistic worldview to integrate socio-psychological models derived from competing theories representing interpretivism and expect valid results. Before jumping into constructing a federation the simulation engineer must ensure that this is the right thing to do to address the sponsor's problem. In some cases, the best way forward may be to live with contradicting models. It is highly unlikely that we will be able to address all problems with one common approach based on a common theory resulting in a consistent federation. It is much more likely that the multi-simulation approach based on multi-resolution, multi-stage, and multi-models envisioned by Yilmaz and colleagues (2007) needs to be exploited to support the analysis of these multi-faceted challenges we are faced with as a community. Some additional aspects, in particular to better address the aspects of uncertainty and unpredictability—simulation systems can never be "magic mirrors" that allow the user to look into a certain future—are addressed in this book, but other problems may never be solvable.

However, some recent criticism on the use of modeling and simulation, as documented by Gregor (2010), may create the danger to throw the baby out with the bathing water. Gregor documents the viewpoint by some experts that the use of mathematical methods for predicting and measuring effects shows a trend toward using metrics to assess the essentially unquantifiable aspects of warfare that reinforces the unrealistic view that warfare is a science rather than an art and a science. As the US Joint Publication 1 states: "War is a complex, human undertaking that does not respond to deterministic rules!" As will be shown in this book, there are plenty of tools either that can be used in an orchestrated tool set to address these challenges together with defense modeling and simulation approaches or that can be integrated into the simulation systems to provide the necessary functionality to the simulation solution. While war is complex and does not respond to deterministic rules, the engineering principles of combat modeling and distributed simulation provide the means to reduce the complexity and manage uncertainty in support of the military decision maker and will enable better decisions for the management as well as on the battlefield.

As is well known in the engineering management community, three things are needed to ensure success of an approach: (1) *technical maturity* of the proposed solution—if it does not work properly it will not be applied more than once; (2) *supporting management processes*—if the manager does not support the use, it is not going to last long; and (3) an *educated workforce*—if nobody has been taught how to use it, it cannot be applied beyond the scope of a limited group of experts. With this book I hope to contribute to a better education of the workforce by providing a compendium that is state of the art to the simulation engineer in education and hopefully for practitioners in the field as well.

I would like to thank everyone who contributed to this book and hope that each reader finds in the following chapters at least the core of what he is looking for. I hope for feedback to continuously improve this book and keep it up to date to serve the community and the soldiers they support.

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