Model-Based Systems Engineering Approach to Distributed and Hybrid Simulation Systems

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MODEL-BASED SYSTEM ENGINEERING (MBSE) APPROACH TO DISTRIBUTED AND HYBRID SIMULATION SYSTEMS

by

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ABSTRACT

INCOSE defines Model-Based Systems Engineering (MBSE) as “the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.” One very important development is the utilization of MBSE to develop distributed and hybrid (discrete-continuous) simulation modeling systems. MBSE can help to describe the systems to be modeled and help make the right decisions and partitions to tame complexity.

The ability to embrace conceptual modeling and interoperability techniques during systems specification and design presents a great advantage in distributed and hybrid simulation systems development efforts. Our research is aimed at the definition of a methodological framework that uses MBSE languages, methods and tools for the development of these simulation systems. A model-based composition approach is defined at the initial steps to identify distributed systems interoperability requirements and hybrid simulation systems characteristics. Guidelines are developed to adopt simulation interoperability standards and conceptual modeling techniques using MBSE methods and tools. Domain specific system complexity and behavior can be captured with model-based approaches during the system architecture and functional design requirements definition. MBSE can allow simulation engineers to formally model different aspects of a problem ranging from architectures to corresponding behavioral analysis, to functional decompositions and user requirements (Jobe, 2008).

Dedicado en especial a mi esposa (Thatiana Del Hierro) e hijas (Gabriela & Valerie) por su apoyo incondicional durante este proceso.
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Finally, I will like to thank the all mighty Christ Lord. “I can do all things through Christ which strengthened me” (Philippians 4:13, KJV).

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AHP	Analytical Hierarchical Process
BDD	Block Definition Diagram
BPMN	Business Process Modeling Notation
CONOPS	Concept of Operations
DES	Discrete Event Simulation
DIS	Distributed Interactive Simulation
FOM	Federation Object Management
GHG	Green House Gas
HDDV	Heavy Duty Diesel Vehicle
HLA	High Level Architecture
INCOSE	International Council of Systems Engineers
LCIM	Levels of Conceptual Interoperability Model
LOX	Liquid Oxygen
MBSE	Model-Based Systems Engineering
M&S	Modeling and Simulation
OPD	Object-Process Diagram
OPL	Object-Process Language
OPM	Object-Process Modeling
OPR	Object-Process and Relations
PCP	Panama Canal Pilots
PDU	Protocol Data Unit
PSS	Product-Service System

RPR-FOM	Real-time Platform-Level Reference FOM
RTG'S	Rubber Tire Gantry Cranes
RTI	Runtime Infrastructure
SD	System Dynamics
SCADAS	Supervisory Control Analysis and Data Acquisition Systems
SCOR	Supply Chain Operation Reference
SySML	System Modeling Language
TENA	Test and Training Enabling Architecture
TEUS	Twenty Foot Equivalent Units
TB	Time Bucket
TTU	Tractor Trailer Units
UMIP	Universidad Maritima International de Panama
UML	Unified Modeling Language

CHAPTER 1. INTRODUCTION

Modeling and analysis efforts rise significantly when dealing with complex systems. While parallel and distributed discrete event simulation has been an active area of research for more than thirty years, researchers have until recently focused almost exclusively on fast execution of process and event-oriented models of discrete-event simulations (Rabelo, 2004 and Park, 2005). The advances in this field suggest that distributed simulation and hybrid simulation may play an important role in modeling complex systems for the analysis of these emergent properties. The emphasis of new methodologies for the conceptualization and design of these simulators is to facilitate the engineered approach of different simulation models with other supporting non-simulation applications; as such the architecture must deal with issues related to the coordination of different hardware platforms and components and different software components as noted by Rabelo et al (2004). Requirements and the Life Cycle analysis are very important issues.

Pedrielli et al. (2012) argues that even though commercial simulators can analyze complex networked systems, distributed simulation platforms are needed for the successful implementation of complex systems simulation projects. Commercial-of-the-Shelf (COTS) simulation packages provide a wide range of functionalities that enhance the simulation visualization, run-time support, communications, and animation capabilities among others. However, Uygun (2009) explain that business process are becoming more and more complex and this complexity is leading distributed simulation environments to the need of more sophisticated integration and exchange of information in regard to the development and application of simulation systems.

1.1 Problem Description

Experience has shown that unless the systems-simulation engineer understands the process by which their specifications (itself another interpretation of the customer requirements) is implemented the distributed simulation system is prone to failure. In addition, the traditional way in industrial engineering of simulation has focused on the implementation of a software package and not of a system with the respective life cycle. This last approach cannot be scaled up to distributed and hybrid simulation systems which are more related to model complexity. With systems engineering modeling languages such as SysML and adoption of system engineering lifecycle methods that are intuitive in its usage these two problems can be alleviated.

However, literature show that well-structured process modeling techniques that combine expressiveness, simplicity and formal semantics are being used in the implementation of hybrid and distributed simulation systems but the absence of standard business process modeling concepts present challenges in their use for system developments (Van der Aalst, 2004)

Recent research studies have emerged proposing methodological frameworks for conducting simulation studies in very particular areas and with a specific paradigm (i.e., agents, discrete-event, system dynamics). In particular, Santa-Eulalia (2012) proposes a methodological framework for the modeling and simulation of agent-based advanced supply chain planning systems. Their research specifically denotes that the literature is lacking an integrated framework covering all the phases of a modeling and simulation process and depicts a gap in the literature particularly concerning the analysis phase. Santa-Eulalia et al (2011) argue that no specialized methodological framework for analyzing simulation in the context of Supply Chain (SC) planning has been defined in the literature. Their research aims at defining a uniform representation of distributed SC planning systems to assist simulation analysts in the definition and implementation of functional requirements in possible simulation scenarios.

1.2 Relevance of Research

Designing and building a distributed simulation system (DSS) is a major undertaking requiring much work from experts in a variety of disciplines. The ultimate quality of the system depends on how well the system meets the needs of the users. A simulation development roadmap for the lifecycle development of distributed simulations on which the particular plans are built is required. The application of such a roadmap has the benefits of:

- Visibility and understanding of the system under development, making clear the advantages and limitations of what will be developed
- Development of a coherent, consistent and maintainable system specification,
- Use of an industry-standard model notation to capture the analysis and design, enabling portability of the design to other tools and products,
- Flexibility in catering for evolving requirements,
- Development of testable requirements, enabling original functionality to be re-checked after addition of enhancements,
- Techniques for enabling the re-use or replacement of modules with defined interfaces,
- Easy and maintainable connections between specification and implementation,
- High initial quality and low rework costs.

In addition, advances in simulation and modeling techniques suggest that distributed simulation and hybrid simulation may play an important role in modeling complex systems for the analysis of business enterprises. Helal (2008) proposed a simulation methodology that combines System Dynamics (SD) and Discrete Event Simulation (DES) paradigms to define a hybrid discrete-continuous approach to simulate the business enterprise. This particular approach is called the SDDES Enterprise Simulation Model (see Figure – 1.2). The SDDES methodology implements a synchronization algorithm in order to keep the statistical validity of each individual simulation method. The combination of these two simulation methods provides a hybrid simulation platform in a distributed simulation like arrangement that enables the modeler to implement the simulation in modular format to fully take advantage of the system dynamics and discrete event simulation capabilities.

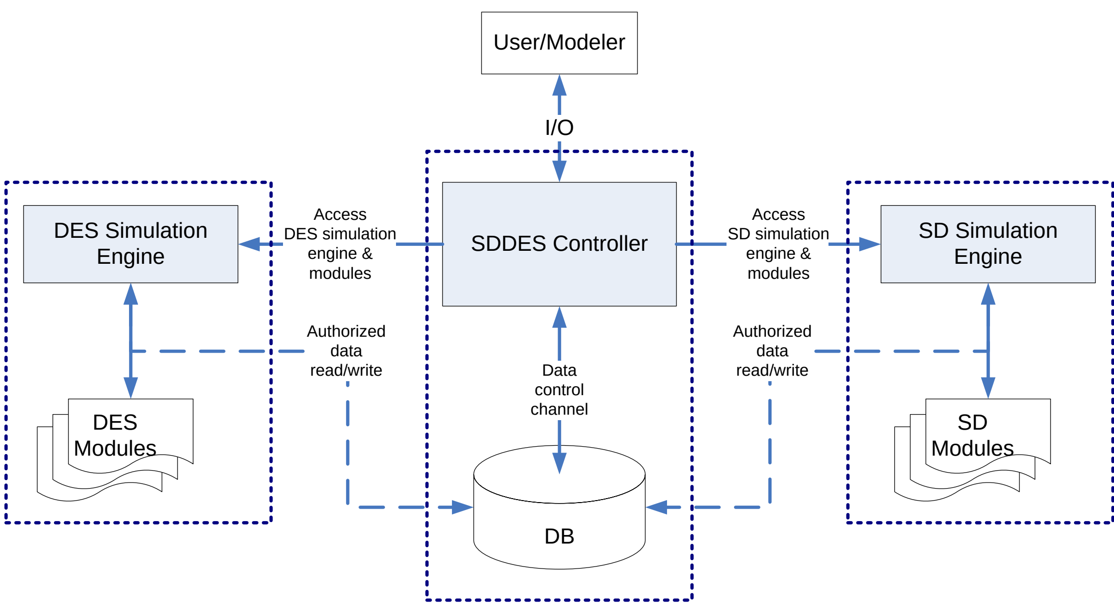


Figure 1-1: Schematic diagram of the SDDES controller test bed implementation (Helal, 2008)

However, we would like to clarify that the majority of hybrid simulation studies in the literature are just concern with the design and implementation of the simulation and not in the analysis or functional requirements modeling that can ensure the adequate business scenario modeling and results.

1.3 Our Approach

Santa-Eulalia (2012) developed the FAMASS methodological framework that comprises of four interactive modeling approaches as described in Figure – 1.1. The FAMASS framework adapted the use of use case diagrams as defined by the unified modeling language (UML) and SysML requirements diagrams as defined by the Object Management Group (OMG 2010). These modeling languages will be used as we defined our distributed and hybrid simulation development roadmap. The Systems Modeling Language (SysML) will aid in the definition of the initial analysis and modeling approach for the modular-based composition of our roadmap to map the business enterprise processes directly to the continuous and discrete modules as we comprised our hybrid simulation approach.

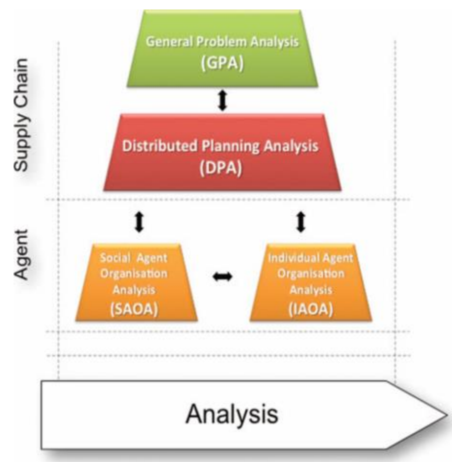


Figure 1-2: Four main modeling approaches proposed of analysis of SC and agent levels for simulation purposes (Santa-Eulalia, 2012)

Our research will focus on defining an integrated simulation development roadmap in the context of distributed and hybrid simulation modeling practice of business enterprises. More specifically, our integrated simulation development roadmap will aim at defining modeling and analysis techniques of conceptual requirements for conducting distributed and hybrid simulation studies of business enterprises and their functional requirements in terms of implementation in a Model-Based Systems Engineering (MBSE) development approach.

In addition, due to the advancements in technology today agent-based systems represent a promising technology for modeling and simulation of complex systems (Cicirelli et al, 2009). Our research efforts extend the adoption of agent-based system by proposing the definition of hybrid simulations methods with SDDES capabilities. Hybrid simulation systems can incorporate the computational aspects and communication capabilities introduced by agent-based simulations into a simulation framework to interact with the continuous and discrete system models.

Our aim is at the definition of a simulation development roadmap that integrates the traditional system engineering lifecycle models with the enhancement of newly define MBSE methodologies to obtain the development flexibility required to define accurate business scenarios and cases for better business system developments. Using SysML models, a methodology is described to obtain an understanding of the problem, identify and develop potential solutions, analyze them, and suggest the best alternative. This integration uses existing concept development tools with MBSE developments methods in order to create appropriate system architectures. This system architecture has the right partitions and definitions to allocate behavior to structure.

1.4 Potential Contributions

The anticipated contributions of this research work include the followings:

1. The utilization of MBSE to design and architect distributed simulation systems is very unique. This contribution is important in order to alleviate the problems with the current methodologies for distributed simulation.
2. A new roadmap for the implementations of conceptual modeling techniques that can leverage from MBSE methods and tools for achieving adequate interoperability levels in in distributed and hybrid simulation systems.
3. Another contribution is requirement prioritization. The priorities are used in trade studies to select system concepts. Input from the stakeholders is very important in order to define this.
4. An approach to enhance the usability of distributed simulation in modeling complex systems and overcoming the challenges it is currently facing.

1.5 Dissertation Organization

In the followings, an overview of the different chapters of this dissertation is provided. Chapter 1 discusses problems, challenges, and potential contributions in distributed and hybrid simulation developments. Life cycles and the traditional industrial engineering approach are introduced. We reviewed the related work and outlined the organization of this dissertation.

Chapter 2 starts with a comprehensive description of the different methodologies used for Model-based systems engineering. This description included the evolving nature of systems engineering methodologies and its importance in the building of systems. We focus on the different contributors in the domains of distributed and hybrid simulations. Chapter 2 ends with a gap analysis to justify this research endeavor.

Chapter 3 presents the research methodology and its unique steps. These steps consider the logic and the validation of the proposed utilization of MBSE for distributed and hybrid simulations. Case studies are going to be one of the major instruments to be used during this research work. Another aspect is the utilization of a survey instrument to gather expert's opinions in the field of distributed and hybrid simulation and systems engineering.

Chapter 4 will describe the methods and procedures used to accomplish our survey study. Survey constructs and items will be established in terms of MBSE characteristics for proper requirement analysis and architectural system design developments of distributed and hybrid simulation systems. The data collection and results analysis will be presented in Chapter 5. The survey constructs and items responses from the expert opinions will aid in the development of a simulation development roadmap that will consider leading MBSE methods and tools.

Further, based on the expert opinion a simulation development roadmap for architecting and design of distributed and hybrid simulation systems will be defined in Chapter 6. The developmental roadmap and guidelines will be evaluated through the implementation of two case studies described in Chapter 7 and Chapter 8. Chapter 9 presents the conclusions and contributions of this work and suggests directions for further research. The contributions of this research are numerous. Directions for further research are very important and our limitations are acknowledged one more time.

CHAPTER 2. LITERATURE REVIEW

This chapter presents the literature survey of previous work regarding model-based systems engineering (MBSE), hybrid simulation, and distributed simulation. The chapter ends with an analysis gap that supports our research.

We believe that MBSE can help analysts and developers in the conceptualization efforts and definitions of interoperability characteristics and functional requirements needed for the successful implementation of distributed and hybrid simulation systems for business enterprises. Further, MBSE can allow simulation engineers to formally model different aspects of a problem ranging from architectures to corresponding behavioral analysis, to functional decompositions and user requirements (Jobe, 2008).

This chapter starts with the definitions of systems engineering and the basic methodologies that concentrated in software development. These software methodologies evolved in MBSE methodologies that are described next. This description included the evolving nature of systems engineering methodologies, formal definitions in the industry and its importance in the building of systems. Then, some of the recent work in hybrid simulation and distributed simulation relevant to our research area is presented. Finally, a comprehensive gap analysis is performed to justify the proposed utilization of MBSE for the analysis, design and implementation efforts of distributed and hybrid simulations systems.

2.1 Systems Engineering

The term Systems Engineering means different things to different groups. The classical view of systems engineering leans toward being a way of thinking or approach to design, whereas recent definitions term it as an engineering discipline. There have been numerous definitions of systems engineering presented over the years and they are shown in Table 2.1. The table shows that the definitions have evolved over the last 40 years to include the role of in systems engineering and the increasing importance of life cycle considerations. This increased importance of life cycle is very important for simulation systems.

The definition used in this research is the one provided by The International Council of Systems Engineers (INCOSE). INCOSE defines systems engineering as a "interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Cost & Schedule, Performance, Training & Support, Test, Disposal & Manufacturing".

Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs." (INCOSE 2004). This definition is based on the overall perspective of the entire lifecycle development process of a system or product. System development efforts need to consider interactions between system components and conduct system requirement definitions based on customer needs and overall system functional characteristics.

Table 2-1: Definition of Systems Engineering. (Adapted from Tepper 2010)

Source	**Definition of Systems Engineering**
Mil-Std 499A (1974)	The application of scientific and engineering efforts to: (1) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (2) integrate related technical parameters and insure compatibility of all related, functional and program interfaces in a manner that optimizes the total system definition and design; (3) integrate reliability, maintainability, safety, survivability, human, and other such factors into the total technical engineering effort to meet cost, schedule, and technical performance objectives.
Chase (1974)	The process of selecting and synthesizing the application of the appropriate scientific and technical knowledge to translate system requirements into system design and subsequently to produce the composite of equipment, skills, and techniques that can be effectively employed as a coherent whole to achieve some stated goal or purpose.
Sailor (1990)	Both a technical and management process; the technical process is the analytical effort necessary to transform an operational need into a system design of the proper size and configuration and to document requirements in specifications; the management process involves assessing the risk and cost, integrating the engineering specialties and design groups, maintaining configuration control, and continuously auditing the effort to ensure that cost, schedule, and technical performance objectives are satisfied to meet the original operational need.
Wymore (1993)	The intellectual, academic, and professional discipline the primary concern of which is the responsibility to ensure that all requirements for a bioware/hardware/software system are satisfied throughout the life cycle of the system.
Ramo (1993)	A branch of engineering that concentrates on the design and application of the whole as distinct from the parts…looking at the problem in its entirety, taking into account all the facets and variables and relating the social to the technical aspects.
INCOSE - International Council on Systems Engineering (2004)	An interdisciplinary approach and means to enable the realization of successful systems. If focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.

2.1.1 System Lifecycle Models

Estefan (2008) explains that in the system engineering community a number of lifecycle models for software and large-scale systems developments have been used in government, industry and academia. These system engineering lifecycle models are: (1) the waterfall model, (2) the "Vee" or V-Model, and (3) the spiral model which each of them along with some variations have been used extensively in industry. Estefan (2008) further notes that the waterfall and spiral lifecycle models have been used as support structures for system design and the V-Model as an incremental and iterative system development tool. These models have been analyzed by the systems engineering community in order to evolve their own methodologies. In addition, it is possible to say that SysML has emerged as a powerful alternative.

Pezzotta et al (2012) reviewed the systems engineering lifecycle models for the development of a Product-Service System (PSS) in the service engineering domain. He explains that service engineering is an interdisciplinary domain and it requires an integrated approach to its development as it requires expertice in the constructive models of engineering and service design aspects. In addition, he expresses in his review that the software engineering "Waterfall" model shown in Figure – 2.1 is the lifecycle model most widely used in the service engineering and was first introduce by W.W. Royce in the 1970 (Pezzotta, 2012 & Boehm, 1988).

Royce (1970) describes the Waterfall model as a sequential development process that evolves through the phases of requirement analysis, design, implementation, testing and validation, integration and maintenance. This model was first developed for design and development of Large-Scale Software systems and it was described as a gate-based model in which you can only proceed to the next phase only after completing and validating the current phase.

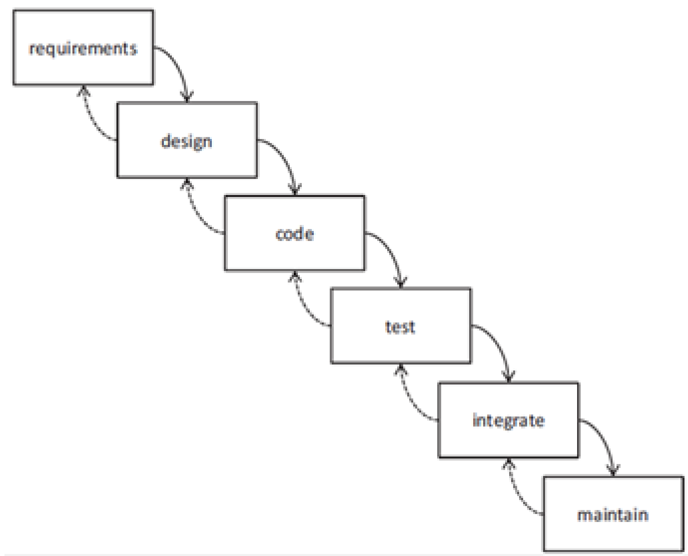


Figure 2-1: The Waterfall Model (Boehm, 1988)

In contrast to the Waterfall model, another perspective in lifecycle models is the system development model called the "Vee" model which emerged on the notion that a mirrored effort to the design steps should be define for testing (V-Model, 2004). Pezzotta (2012) in his review describes that the left branch of the V-Model emphazises in project and planning definition as the right branch defines validation and verification methods aling with the left branch development phases. The "Vee" Model is particularly design to guide software engineers in planning and executing projects taking into consideration the entire life cycle of the system (V-Modell, 2004). London (2012) notes that the V-Model describes what the systems engineering community knows as "concept of operations" (CONOPS) as a basis of any product or system development process. Figure – 2.2 illustrate the concept of the V-Model lifecycle model.

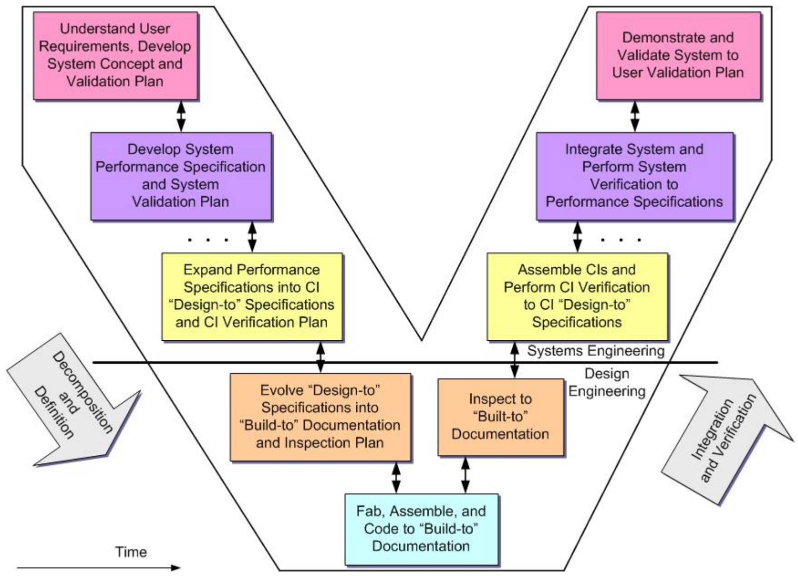


Figure 2-2: "Vee" or V-Model (Estefan, 2008)

Pezzotta et al (2012) describes the Spiral Model as a "risk driven process model generator that is used to guide a multistakeholder concurrent engineering of systems" (p. 216) as introduce by Boehm in 1988. Boehm & Hansen (2001) note the adoption of the concept of "evolutionary acquisition" by the Department of Defense as a acquisition strategy framework. They further describe the spiral development model to have two main development approaches: (1) a cyclical approach – an incremental development process for system design definition and implementation while decreaseing risk levels during development and (2) anchor point milestones approach – which ensures a commitment to feasible and mutually satisfactory system solutions by stakeholders and developers.

Further, Pezzotta et al (2012) proposed the spiral development model for a Product-Service System (PSS) definition in the service engineering domain. His proposition details the advantages of the spiral development model as its engineering process and phase iteration characteristics can incorporate customer involvement with a comprehensive lifecycle perspective.

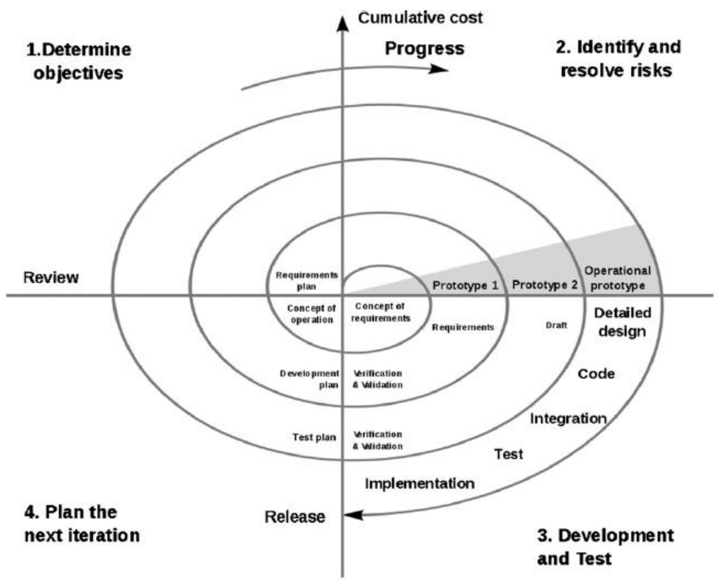


Figure 2-3: Spiral Model (Boehm & Hansen, 2001)

In addition, London (2012) discusses advantages in the use of the spiral development model specially at the initial cycles of development as in certain system or product design efforts a full set of requirments cannot be define prior to system design. In this case the author points out that the risk driven approach of the spiral method can be prove useful in evaluating the aspects of the design with most risks in terms of immature technology and/or new raw material selection.

Another system engineering practice in which system lifecycle developments have been seen is on the government-domain as a system acquisition method. London (2012) in a literature review discusses the application of lifecycle models for acquisition in the United States

Department of Defense (DoD) as a structured management process that has defined discrete phases separated by major decision points called milestones. Figure – 2.3 depicts the DoD Lifecycle Framework (Estefan 2008).

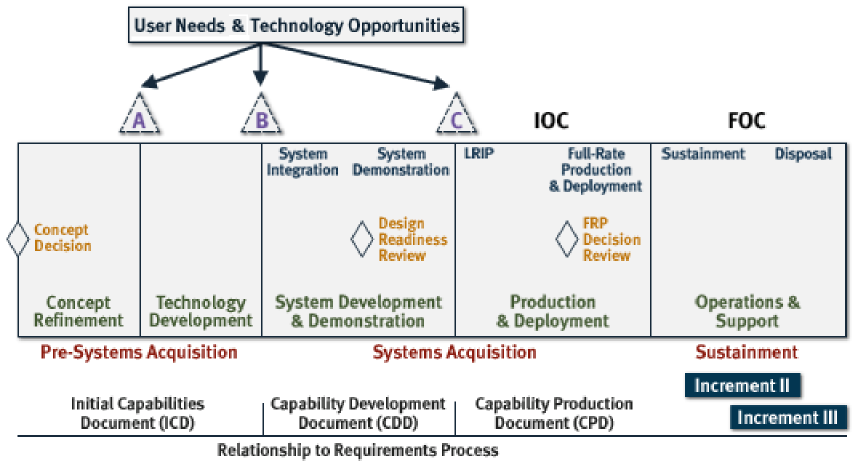


Figure 2-4: U.S. DoD Lifecycle Framework

2.2 Systems Engineering Modeling Languages

The object management group (OMG) is the governing body that monitor and guides the development of the SysML modeling language. Figure – 2.4 below provides a general overview of the natural composition of the SysML modeling language which in fact reuses and extends the unified modeling language (UML) in order to specify, analyze, design, and verify complex systems development (OMG SysML 2008).

SysML extension of the UML modeling language provides a number of essential semantic type graphical representations that define the groundwork for modeling any type of system hierarchy and system component classification as shown on Figure – 2.5.

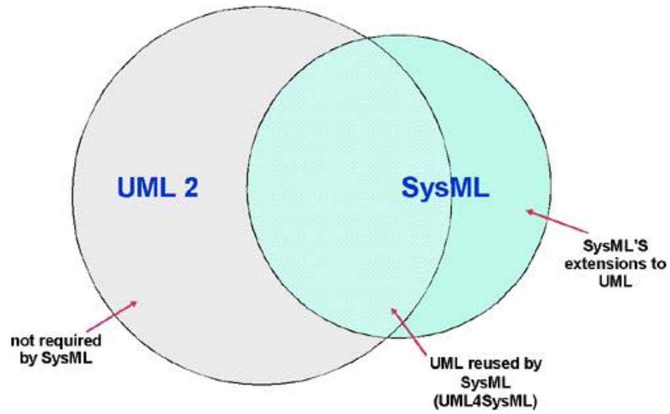


Figure 2-5: Relationship between SysML and UML (OMG SysML 2008)

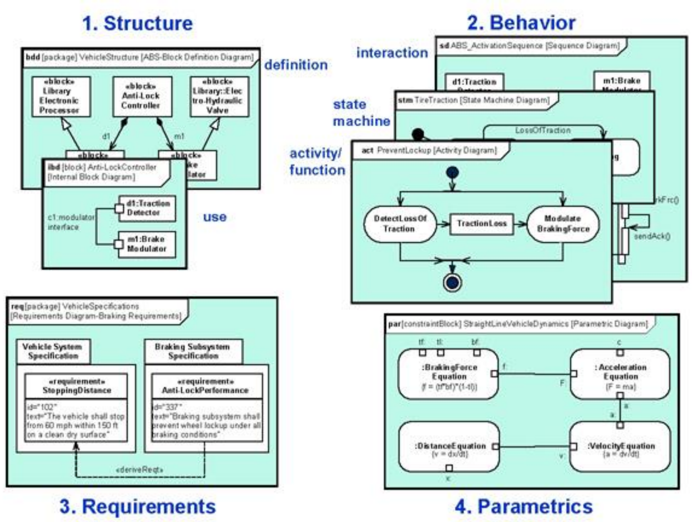


Figure 2-6: The Four Pilars of SysML (OMG SysML 2008)

The structure diagram can represent hardware, software, facilities personnel, or any type of system elements. The behavioral diagrams inherit all of the UML notations for use case diagram, activity diagram, sequence diagram, and state machine diagram. This facilitates the modeling of interaction between systems and systems parts. With the requirements diagrams a bridge between the typical requirements of management tools and the simulation model is established to allow the modeler flexibility when defining system policies and requirements.

Finally, the parametric diagram provides the ability to define constraints on system property values such as performance, reliability, and mass properties to integrate and communicate with the different business process as we model the business enterprise as a whole (OMG SysML 2008).

SysML is geared toward incrementally definable description of conceptual system design and product architecture as describe by Balmelli (2006). SysML parametrics concept is founded in part on a theory called composable objects (COBs). Composable objects have been developed at the Georgia Institute of Technology (GIT) as a means for representing and integrating design models with diverse analysis models. The COB representation is based on object and constraint graph concepts to gain their modularity and multi-directional capabilities (Peak et al, 2007). Figure – 2.6 is an example of a mechanics of material analysis building block SysML parametric diagram.

The parametric and requirements modeling are the only two modeling structures that were introduced as new constructs in the SysML development for modeling systems complexity through the extension of the UML standards. The enabling of requirements modeling and the support to parametric modeling introduces the capability to enrich distributed and hybrid simulation systems and support the approach of MBSE methodologies and their structures to improve the efficiency of simulation and modeling of complex systems as a whole.

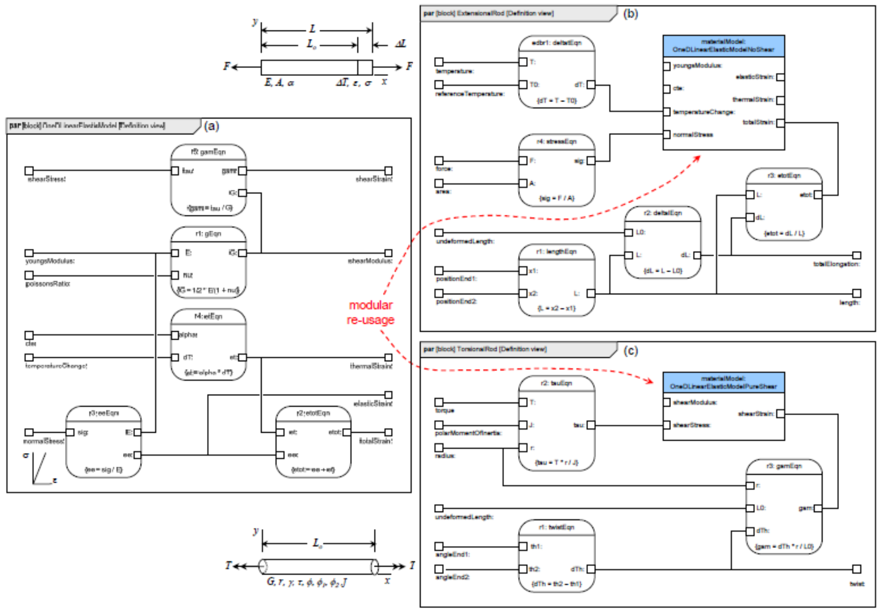


Figure 2-7: Example of Mechanic of Materials Analysis Building Block SysML Parametric Diagram (Peak et al, 2007)

Colombo et al (2007) explores the capabilities of SysML as a modeling language to integrate with the problem frames concept. This concept is applied in the software development domain to establish relationships of system requirements to real world behavior characteristics not to software functions characteristics. Colombo et al (2007) explains that the ability of SysML to extend activity diagrams “support domain decomposition into simpler structures” (p. 30) which expands the inherent capabilities of UML modeling structures.

Wang and Dagli (2008) study transformation techniques to convert SysML model specifications into Colored Petri Nets to enable guided executable structured architectural process designs. Wang and Dagli (2008) noted that the defined framework and methodologies used in their work establishes a generalized approach to executable system architectures for concurrent design of discrete event systems.

Kwon and McGinnis (2007) demonstrate how SysML "overcome limits of UML from the perspective of system engineering" (p. 1075). The implemented framework explains how geometric data can be incorporated into the simulation by the ability of the SysML to define requirements into the model, which are not present in the UML modeling characteristics. Kwon and McGinnis (2007) further explain that information systems in a manufacturing environment are very complex and since simulation tools generate and consume data the integration with other system application can be a challenge. SysML ability to model information instances was valuable in Kwon and McGinnis (2007) work because it provided a step forward in the integration of factory simulation modeling with critical manufacturing data sources. McGinnis et al (2006) describe the implementation of the SysML parametric modeling capability in data interexchange of a semiconductor wafer fabrication and manufacturing process simulation. Huang et al (2008) also explore the capabilities of SysML to support executable modeling architectures in a manufacturing process simulation study. Huang et al (2008) defines a simulation framework that is able to describe both the application domain and the analysis domain using the SysML modeling language.

2.3 Model-Based Systems Engineering

INCOSE defines Model-Based Systems Engineering (MBSE) as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." In accordance to NASA (2007) System Engineering Handbook , "a system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behavior, and performance."

Modeling and analysis efforts rise significantly when dealing with complex systems. Balram (2012) notes that "Model-based systems engineering (MBSE) is a cutting edge, evolving practice for the development of complex projects" (p. 10). Advances in simulation and modeling techniques suggest that distributed simulation and hybrid simulation may play an important role in modeling complex systems for the analysis of business enterprises. The systems engineering community has started to adopt the MBSE process, tools and methodologies for modeling complex systems (Estefan, 2008). Without a formal approach to modeling and analysis of complex enterprise processes systems engineers will face future levels of complexity in industrial systems that it will be extremely difficult and costly to solve effectively and in a timely manner.

Expanding upon the INCOSE definition, MBSE is a methodology where models are central to the specification, design, integration, verification and validation of systems (Estefan, 2008). A survey was conducted in the most common system engineering MBSE methodologies and tools by Estefan (2008) in which he differentiated methodologies between processes, methods, and lifecycle models. His work goes to evidence that practitioners loosely interchange the word methodology with the word process. Figure – 2.7 depicts the relationships between process, methods, tools and environments (PMTE) and how these PMTE elements or factors have an effect on technology and people as discussed by Martin (1996).

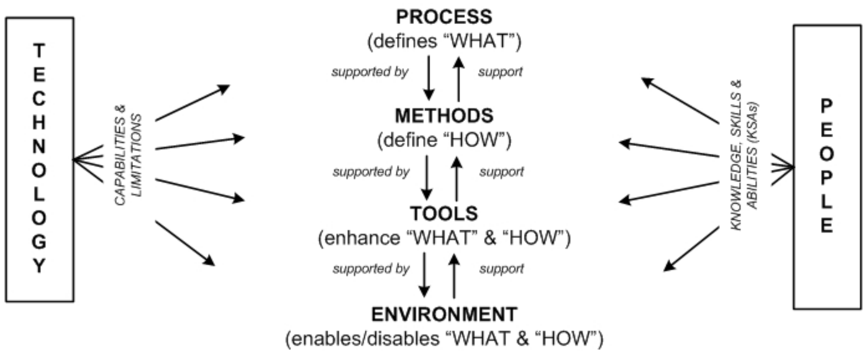


Figure 2-8: PMTE Elements in MBSE Methodologies: Process, Methods, Tools & Environment (Estefan 2008, Martin 1996)

Estefan (2008) survey of MBSE methodologies notes that acknowledging the effect of PMTE elements in technology and people lead to the successful implementation of MBSE methodologies into large-scale development of complex systems within organizations. In addition, his work presents the definitions of PMTE Elements as stated by Martin (1996), see Table – 2.2.

Also, Martin (1996) states that technology capabilities and limitations need to be taken into consideration during system design developments. Estefan (2008) expands on the notion that technology can either hinder or enhance system development efforts. As MBSE methodologies are implemented for the development of complex system designs a proper selection of PMTE needs to be consider as knowledge, skills and abilities (KSA) of team members (Martin 1996), especially during multidisciplinary and collaborative development environments.

Table 2-2: PMTE Definitions (Estefan 2008 & Martin 1996)

Process - "P"	Is a logical sequence of taks performed to achieve a particular objective. Defines the "WHAT" is to be done and the "HOW" each task is performed.
Method - "M"	Consists of techniques for performing a task. It defines de "HOW" of each task.
Tool - "T"	An instrument that can enhance the efficiency of a task. It facilitates the acomplishment of the "HOWs".
Environment - "E"	Consists of the surroundings, the external objects, conditions or factors that influence the behaviour and actions of an object, person or group. An environment can enable or disable the "WHATs" and the "HOWs".

London (2012) expresses the importance of collaboration of multidisciplinary teams in the development of complex systems due to the fact that all members of the team must have a common understanding of the design and customer requirements. In addition, Graignic (2013) supports the notion that a multi-disciplinary approach is needed in complex systems designs and implementations as they require particular data structure modeling efforts to capture all behavioral interactions within the system.

Several MBSE methodologies have been developing throughout the years in support to the systems engineering lifecycle development models in the systems engineering practice. Based on our literature review and supporting literature survey of leading MBSE methodologies (Estefan, 2008) we have decided to present the OOSEM, Vitech STRATA, Rational Harmony and the OPM methodologies as candidates for the support of distributed and hybrid simulation implementations in business enterprises.

2.4 Object Oriented Systems Engineering Method (OOSEM)

The Object-Oriented System Engineering Method integrates a top-down systems approach which integrates object-oriented methods and modeling concepts. The methodology was first developed under a joint effort between Lockheed Martin Corporation and Systems & Software Consortium endeavor in 1998. London (2012) expresses that the OOSEM methodology approach is derived from standard system engineering activities associated with the "Vee" system engineering development model.

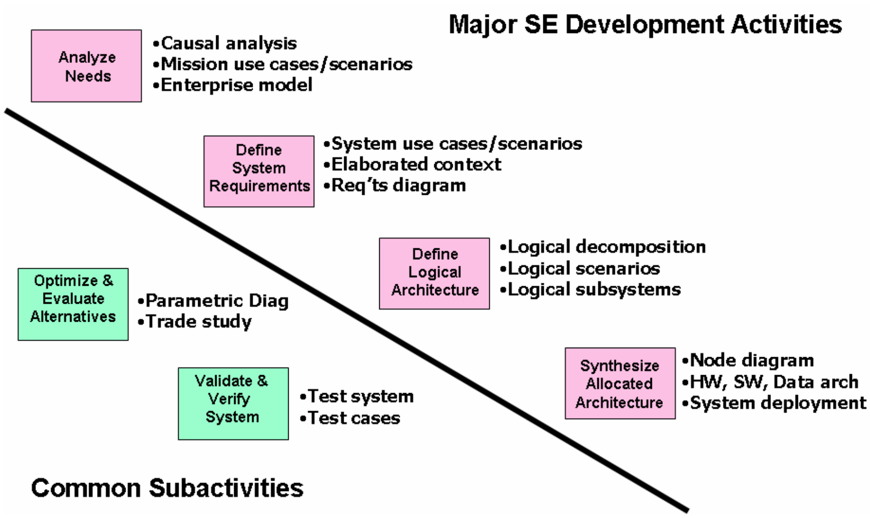


Figure 2-9: OOSEM Activities and Modeling Artifacts (Estefan 2008)

Wolfrom (2011) explains that the OOSEM methodology support requirements analysis through the development, evaluation and verification of complex system by defining Use Cases and Scenario-Driven design strategies. Figure – 2.8 depicts four primary phases: (1) Analyze Stakeholder Needs, (2) Define System Requirements, (3) Define Logical Architecture and (4) Synthesize Allocated Architecture. These major systems engineering activities help the system development teams in the gathering of stakeholder needs using use cases to the define scenarios and system problems. Subsequently, requirements and measures of effectiveness are developed to ensure that system functional characteristics match stakeholder needs. Estefan (2008) describes in his review that the OOSEM methodology predominantly utilizes the SysML modeling language to represent the various artifacts generated through the system development process.

In addition, as subsystem designs are implemented and verification/validation efforts are conducted an iterative requirement analysis is required on the overall system to perform optimization and evaluation of design alternatives. Estefan (2008) also states that system engineering practitioners find affinity to this method due to the structural decomposition generated by system activity and state diagrams during the system development process.

2.4.1 Vitech MBSE Methodology

The Vitech Corporation developed a model-based system methodology called STRATA. The name STRATA is an abbreviation for “strategic layers”. Vitech (2011) describes the STRATA methodology as an MBSE approach based on a “layered” development process for analyzing and solving system design problems. STRATA was developed by John Long, Marge Dyer and Mark Alford along with other Vitech Corporation colleagues. Figure – 2.9 illustrate the MBSE perspective of the Vitech approach.

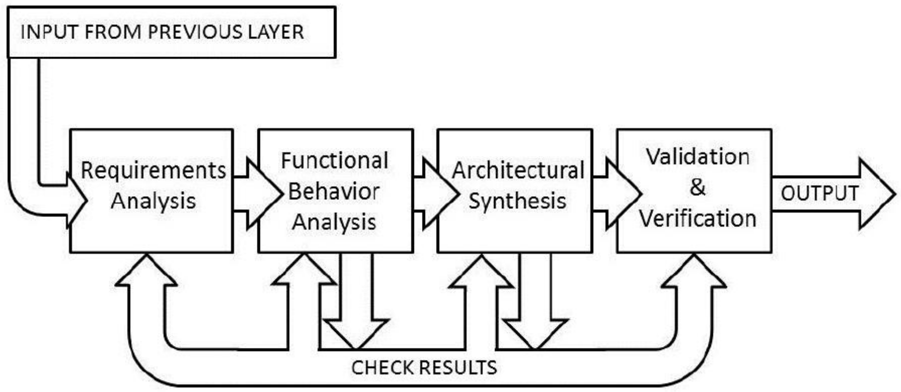


Figure 2-10: Vitech MBSE Methodology (Vitech, 2011)

The layered approach described by Vitech (2011) is the heart of the MBSE perspective to the system development process. The STRATA methodology is compared to an "onion peal" approach in which during the system analysis and definition the design team assures that all aspects of the engineering problem is addressed completely and consistently throughout the entire system development process.

London (2012) reviewed MBSE methodologies and notes that the STRATA methodology seeks to avoid the cycle of rework and fixing errors early in the design process by ensuring constraints are verified and validated properly during the development process. Vitech (2011) avows that the STRATA layered approach makes the design process "virtually fail safe".

2.4.2 Rational Harmony for Systems Engineering

The Rational Harmony for systems engineering is a subset of the overall Rational Harmony development methodology and as seen in Figure – 2.10 the methodology follows the systems engineering "Vee" lifecycle development model (Hoffmann, 2011). The Rational

Harmony method was originated by I-Logix, Inc. but became part of IBM via company business acquisition.

The key system engineering objectives in the Harmony methodology are to derive the required system functions, identify the system states, and allocate these behaviors to subsystem structures (London, 2012). The methodology is divided into three high level activities: (1) requirement analysis, (2) functional analysis, and (3) design synthesis. The requirement analysis in this methodology requires the system design team to gather stakeholder's system or problem information in the form of documents and/or through stakeholder's interview process.

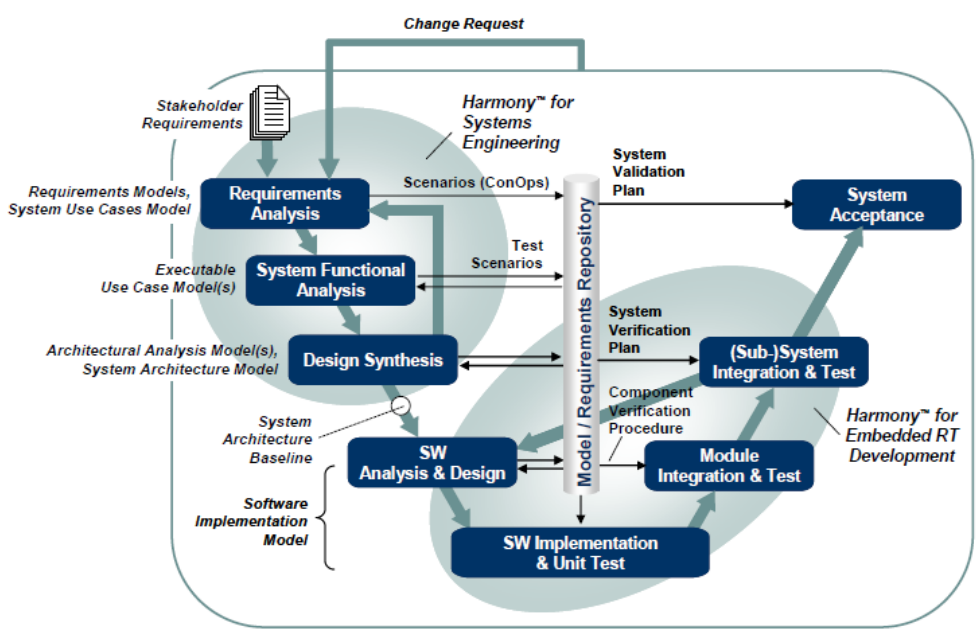


Figure 2-11: Rational Harmony Integrated Systems/Embedded Development Process (Hoffmann, 2011)

Once system requirements are derived from stakeholder's each one of the requirement are developed into use case scenarios. The Harmony method focuses in system functional analysis via a "service request-driven" modeling approach along with the SysML system modeling language (Hoffmann, 2011). Estefan (2008) discusses that for each top-level process in the Harmony methodology detailed design process flows are developed through SysML activity, sequence or state diagrams. Activity diagrams are generated first and Harmony methodology tools facilitates the automatic generation of sequence diagrams. This methodology uses data repositories based on system characteristics and requirements in order to generate appropriate solutions in accordance with selected concepts in the design development process.

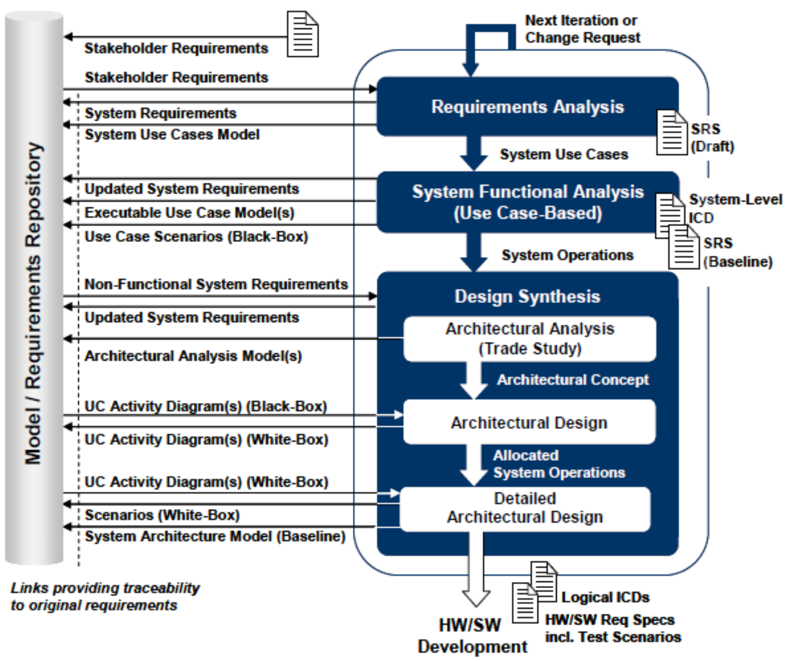
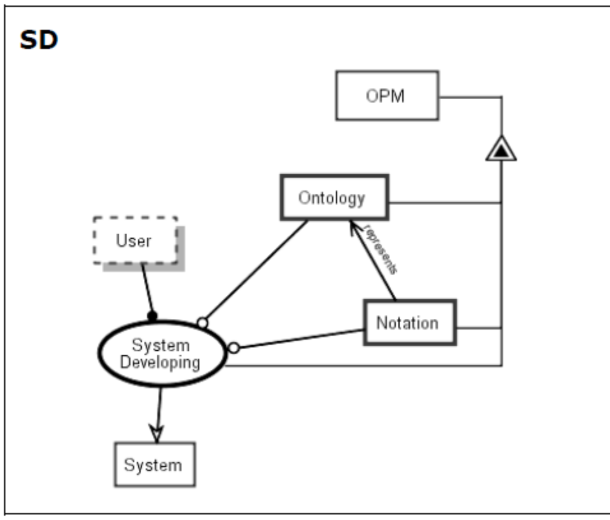


Figure 2-12: Harmony Model-Based System Engineering (Hoffmann, 2011)

Figure – 2.11 illustrates the MBSE approach of the Harmony methodology in order to develop candidate system design solutions and performs trade studies to select one of the alternative generated by the methodology.

2.4.3 OPM (Object-Process Methodology)

Doris (2002) defines the OPM methodology as a formal paradigm to systems development, lifecycle support, and evolution. The OPM method uses a bimodal approach to systems representation: (1) graphical – via visual models called Object-Process Diagrams (OPD) and (2) ontology & notation – constrained natural language sentences called Object-Process Language (OPL). The OPM modeling language OPL is utilized for describing the functional, behavioral and structural aspects of any given system. Figure – 2.12 illustrates the OPM System Diagram (SD) along with the associated ontology, notation, and the system developing process which describes the top-level specification of the OPM metamodel.



OPM exhibits **Ontology** and Notation, as well as **System Developing**.

Notation represents Ontology

System Developing requires **Notation** and **Ontology**.

System Developing yields **System**.

User is environmental and physical.

User handles **System Developing**.

Figure 2-13: The Top Level Specification of the OPM Metamodel

Reinhartz-Berger & Doris (2005) in a comparative study with UML for modeling Web Application describe the OPM method as a "holistic approach to modeling and evolving systems, views objects and processes as two equally important entities that describe the system's structure and behavior in a single model" (p. 57). Estefan (2008) states the three types of entities in the OPM method and their definitions: (1) object – a thing that exists or has the potential of existence, physically or mentally, (2) process – a pattern of transformation that an object undergoes, and (3) state – a situation an object can be at. Dori (2011) explains that OPM transforms objects by generation, consumption and changing objects states. In addition, Dori (2002) asserts to the holistic systems paradigm nature of the OPM method as is capable of modeling artificial systems, natural systems and systems.

Doris & Reinhartz-Berger (2003) further expand the OPM system development process capability to what they describe as "reflective methodology" as the methodology itself possesses the graphical and modeling language tools to assist system developer in their efforts.

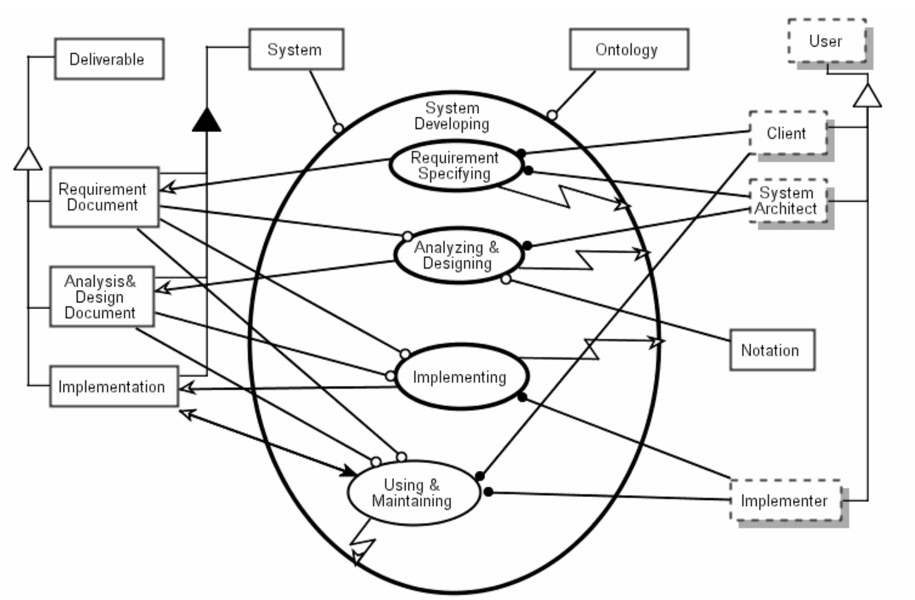


Figure 2-14: OPM System Development Process

The OPM system development process follows the known sequential stages of the system engineering development process: (1) Requirement Specifying, (2) Analyzing & Designing, (3) Implementation, and (4) Using & Maintaining as shown in Figure – 2.13.
Estefan (2008) in his review notes the capabilities inherent by the OPM methodology that enables modeling of system dynamics and control structures in which System Developers can dynamically examine system events, conditions, structural branches and loop at any stage in the development process.

2.4.4 MBSE Developments in Industry

The implementation of Complex Systems designs inherently demands a multi-disciplinary approach in the system implementation as they require particular data structure modeling efforts to capture all behavioral interactions within the system (Graignic, 2013). Graignic (2013) proposed the use of a MBSE methodology to support the behavioral information data model structures considering three major interactions: (1) interactions between component simulations, (2) interactions considering multi-level behaviors (e.g., using components simulation for a module simulation), and (3) interactions between domain behaviors (e.g. thermal characteristics impact on mechanical and/or electrical components).

Garcia (2008) describes Model-based System Engineering as “the practice and discipline within the field of system engineering that models system interactions and interoperability in order to better engineer or develop an intended system design” (p. 63). His work explores a Whole Systems Modeling (WSM) approach to system development by the application of a holonic system engineering view at requirements in terms of processes and interactions. They use the Operational Evaluation Modeling for Content Sensitive Systems (OpEMCSS) through leveraging complex adaptive system techniques and simulations to model system behaviors. Garcia (2008) concludes that by the application of the OpEMCSS in combination with a modified “Vee” system engineering process they were able to provide and define an executable and integrative modeling approach to Whole System Modeling.

Votintseva et al (2011) discusses a model-based approach for system simulation to synchronize early design phases for concept evaluation and functional design. Their work explores the integration of the SysML modeling language and the ModelicaML simulation language to perform requirement evaluations and functional design scenario testing. Their findings show system development advantages in terms of cost and time savings. However, Votintseva et al (2011) concludes that in large industrial projects the use of simulation for early system design evaluation might require different modeling languages and simulation methods (i.e., distributed and hybrid system) due to increasing complexity of industrial system developments needed today.

Votintseva et al (2011) articulates that during a system design conceptualization workflow challenges exists in using system modeling languages (i.e., OMG SysML) as they capture a wealth of discipline-specific information, but few model-driven engineering aspects and information carry out an iterative development process. Author’s point out during their work that the software community has abandoned the traditional “waterfall” or sequential system engineering design approach and that the iterative development process of MBSE methodologies should be adopted in system and product development efforts in industry.

Balram (2012) discusses that "MBSE breaks down the systems engineering process into four primary aspects: functional architecture, behavioral architecture, requirement management, and system validation and verification" (p. 27). Balram (2012) work supports the benefits of applying MBSE on projects for cost estimation and earned value management. He states that the MBSE approach guides the entire project development team to define systems in greater details in the early development phases of the projects.

A Russell (2012) research effort expands on the general notion that MBSE strategies and methods aid in the definition and tracing of requirements in system design elements and processes. He explains that process modeling languages like OMG SysML can easily capture system requirements graphically and enables systems analyst to identify and manage design decision that could impact the overall system costs, technology, supportability and interfaces of design elements characteristics within complex systems conceptualization. In addition, he argues that as system designs grow in complexity the need for more effectively decision support mechanisms are more eminent in the development process. Russell (2012) uses a heavy lift rocket system to exemplify the MBSE approach to model sensor systems used to monitor liquid oxygen (LOX) tanks and its connection to a testing mechanism in the overall rocket system.

2.5 Hybrid Simulation

MBSE methodologies as we have reviewed earlier in this Chapter possesses the modeling characteristics necessary to define and establish a holistic simulation lifecycle approach to distributed and hybrid simulation applications. The Systems Engineering lifecycle development characteristics are potentially beneficial as system modeling languages are particularly effective at capturing business dynamics and their natural process complexities.

This section explains what are hybrid simulations and its importance. In addition, some of the most referenced work is also briefly analyzed. In our discussion we want to establish that "business process simulations" are considered "system simulations" during our literature review in this section as a number of domains in business enterprises like product development, manufacturing systems, service-oriented enterprises, medical-service entities, etc. form part of a big diverse of business enterprises in industry today.

The advancements of technologies have driven both business process modeling and business process simulation methods to develop more integrated solutions. Hybrid simulation methods are becoming a trend in the business process simulation practices. Jahangirian (2010) review of simulation in manufacturing and business explains that distributed and hybrid simulation methods are becoming increasingly popular because of the current trend to provide an enterprise-wide solution. He explains that this trend is driven by a common belief that different parts of an organization will have mutual implications in terms of performance regardless of who is the process owner and has ultimate control over decision-making.

Vergidis et al (2008) explain that a future trend for hybrid modeling techniques that support performance analysis and enable process optimization will be beneficial. According to the author many business process modeling languages spend a lot of effort on describing business complexity through diagrammatic and semantic structures but lack support for the analysis and optimization of business process. Distributed simulation methods provide a platform that can promote the use of business analysis and optimization tools in a hybrid simulation approach. The majority of these hybrid simulation studies are just concern with the design and implementation of the simulation and not in the analysis or functional requirements modeling that can ensure the adequate business scenario modeling and results.

2.4.1 Hybrid Simulation Applications

Rabelo et al (2003) proposed a hybrid simulation framework to integrate system dynamics and discrete event simulations to evaluate the impact of enterprise level decisions to plant operation managers in a semiconductor manufacturing process. Their main focus was to understand the issue of stability in relation to the process performance measures. Rabelo et al (2003) argue that “it is difficult to determine correct control actions to change the system performance due to the high-order non-linear interactions among several interconnected components of the systems” (p. 1126). In addition, other shortcoming in the literature regarding hybrid SD and DES applications is evidence by Brito et al (2011), in which he expresses that what guarantees the advantages of using hybrid simulation applications is not attributed to the independent benefits of the simulation approaches, but by the capacity of integration between the methodologies with the definition of a process of exchange of information and support.

Helal (2008) proposed a simulation methodology that combines System Dynamics (SD) and Discrete Event Simulation (DES) paradigms to define a hybrid discrete-continuous approach to simulate the business enterprise. This particular approach is called the SDDES Enterprise

Simulation Model. The SDDES methodology implements a synchronization algorithm in order to keep the statistical validity of each individual simulation method. The combination of these two simulation methods provides a hybrid simulation platform in a distributed simulation like arrangement that enables the modeler to implement the simulation in modular format to fully take advantage of the system dynamics and discrete event simulation capabilities (Helal, 2008). Helal (2008) adopted the concept of the time bucket (TB) in the development of the SDDES synchronization mechanism that is widely used in the distributed simulation arena. He explains that the TB approach was first introduced by Stienman (1991) as merely a synchronization approach for CIM settings. He also describes that the concept of TB is consistent with continuous simulation approach as a time driven approach and it is not inconsistent with discrete simulation methodology as an event driven approach. In his discussions he points out that several variations of the TB synchronization mechanism have been implements like a variable type TB as defined by Stienman (1992) and a phase TB method as developed by Fujii at al. (1999). A major contribution in his development of the new synchronization mechanism incorporated in the SDDES is that the new mechanism does not use events and does not require one simulation paradigm to dominate the other.

Other hybrid simulation techniques in the literature take on a hybrid analytic-simulation approach. Lee and Kim (2002) address the issue of production and distribution planning with a hybrid analytic-simulation. The authors argue that uncertainty factors like delay, queuing, breakdowns and process operational times can be represented more realistically with a dynamic modeling approach (simulation). Lee and Kim (2002) hybrid analytic-simulation modeling procedures use an interactive approach in which “machine operation time and distribution operation time constraints in the analytic model are considered as stochastic factors and adjusted by the proposed specific process according to the results from the independently developed simulation model which includes general production-distribution planning characteristics" (p. 172).

The integration of agent-based and system dynamics modeling techniques has been combined to define a number of hybrid simulation approaches in the literature. Lattila et al (2010) argues that benefits exist in the combination of these modeling methodologies to create more accurate models. BenDor et al (2009) studied fishery management using an agent based and system dynamic simulation. The authors discuss that ecological sustainability of managed fishery systems omit the effects of economic sustainability in costal geographical areas were the fishing industry is the main employer. Their hybrid simulation approach studies the effects and interrelationships that exist in ecological and economical dynamic systems in terms of sustainability fishery management.

Scholl and Phelan (2004) developed a SD and agent-based hybrid simulation framework to study potential long term performance of organizations. The study takes into consideration the human and social interaction theories to evaluate the argument that certain human organizations are long lived while a private sector firm, on average, ceases to exist two decades after inception. Private firms are subject to internal dynamics that can be study with system dynamics in terms of social, organization and managerial terms and with the use of agent based methods the interrelations and behavioral characteristics can be easily study and defined.

Also, other analytical techniques for business process modeling and decision making have been integrated into hybrid simulation modeling. Rabelo et al (2007) developed a Hybrid SD-DES simulation guided by the supply chain operations reference (SCOR) model to evaluate alternatives in a service and manufacturing global supply chain system of a multinational construction equipment corporation. He argues that “Hybrid SD-DES simulation can support the decision-making process by being able to combine the aggregate and strategic aspects of the value chain system with the very detailed operational levels, in an arrangement that recognize the different needs of the different management levels” (Rabelo et al, 2007, p. 538). Rabelo (2007) uses the analytical hierarchical process (AHP) to incorporate qualitative characteristics in the decision making process which can be of value because it can overcome any potential limitations inherent in the simulation model. The value of integrating AHP into the hybrid simulation is that management process knowledge, experience, preferences and professional assessments affecting the system can be capture by this process and any tradeoffs that can be incorporated in the decision-making process will increase the overall confidence of the decisions and simulation results (Rabelo et al, 2007).

2.6 Distributed Simulation

The definition and the adoption of MBSE methodologies to design and architect distributed simulation systems presents a very unique and important contribution in the application of these simulation systems as it can potentially alleviate the problems with the current implementation methodologies for distributed simulation today. This section presents an introduction of the most-widely use distributed simulation methodologies followed by a discussion of distributed simulation applications in recent years.

In specific, we will discuss the literature regarding the High-Level Architecture (HLA) as a distributed simulation standard, its potential and shortcomings in industry. Uygun (2009) noted that typically middleware software's are needed during HLA based distributed simulation implementations and that system modeling languages are needed to provide a more integrated approach to the design and analysis of business and manufacturing systems. Moreover, Van der Aalst (2004) commented that there are well-structured process modeling techniques that combine expressiveness, simplicity and formal semantics but the absence of standard business process modeling concepts promotes and is the reason for the major differences in business process modeling languages. These literature findings help establish the precedence that a literature gap exists and a potential benefit in the adoption of MBSE methodologies can be define for the implementation of distributed and hybrid simulation systems.

MBSE methodologies, as reviewed earlier in this chapter, make use of the different System Engineering Modeling Languages (i.e., UML, SysML, EFFBD, OPL, etc.) to define functional characteristics, unique system structures and behaviors during system design and development efforts. In addition, the Systems Engineering lifecycle development characteristics inherent in the MBSE methodologies are particularly beneficial in the development and definition of a holistic simulation lifecycle approach to distributed and hybrid simulation applications.

2.6.1 High-Level Architecture (HLA)

The Defense Modeling and Simulation Office (DMSO) first introduced the High Level Architecture (HLA) in 1996 to the Department of Defense (DoD) and it was accepted as an IEEE standard (IEEE 1516) for distributed simulation in September 2000.

The High-Level Architecture supports the development of simulation applications by integrating other simulation components and tools such as visualization tools and real world systems in a common high-level simulation architecture (Kim and Kim, 1998). This architecture promotes interoperability and reusability of legacy simulation models in order to develop a new, complex simulation (Judith et al.,1998). Reuse of existing components may reduce the cost and time required to develop a new simulation.

The HLA defines terms used in the context of distributed simulation as follows. A federate is a member of a federation; a federate refers to an actual simulation, and the role in a distributed simulation is defined in its Simulation Object Model (SOM). Figure – 2.14 shows the configuration of a federation at-a-glance. A federation is a set of simulations (federates) interconnected through the Run Time Infrastructure (RTI); a Federation Object Model (FOM) and its supporting infrastructure are used to form a large model to achieve certain objectives.

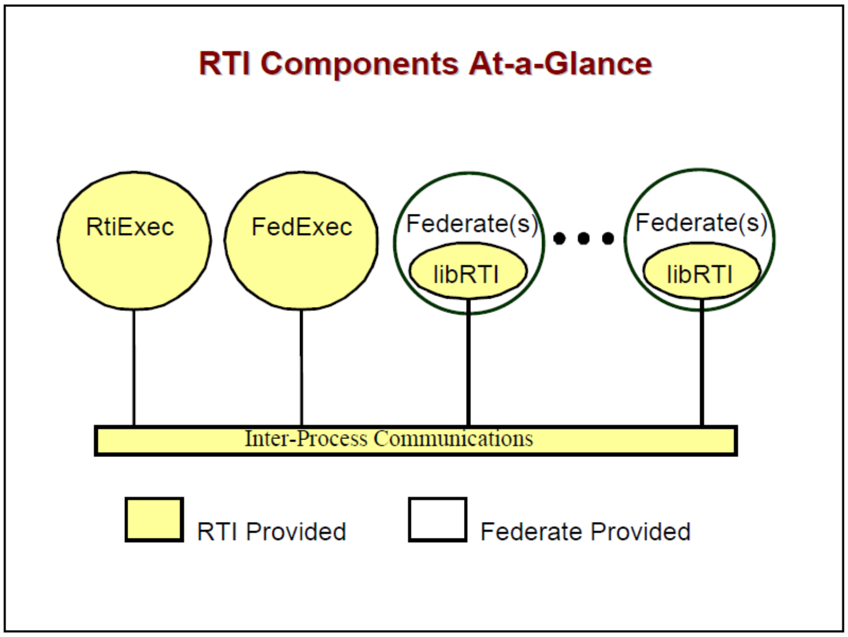


Figure 2-15: RTI Components At-a-Glance (DMSO, 1998)

Interoperability between federates is achieved by three major components: HLA rules, which describe federation and federate responsibilities; the RTI, which coordinates the local simulation time managed by each federate with the global simulation time in a federation and controls the data transfer; and the Object Model Template (OMT) which defines data structure, the format of the federates (SOM), and the common information in federation (FOM) (Judith et al, 1998).

The Run Time Infrastructure (RTI) is a software implementation of the HLA Interface Specification, which defines the common interfaces for distributed simulation systems during the execution of an HLA simulation. While the federate code provides the internal functionality of the simulation, the local RTI Components (LRC) provide the RTI services specified in the Interface Specifications through the RTIambassador class and assist the federate in communicating with the RtiExec and the FedExec (Jaebok, 2005). Figure -2.15. Illustrates RTI and Federate Ambassador components in a typical federate configuration that can form part of a simulation architecture.

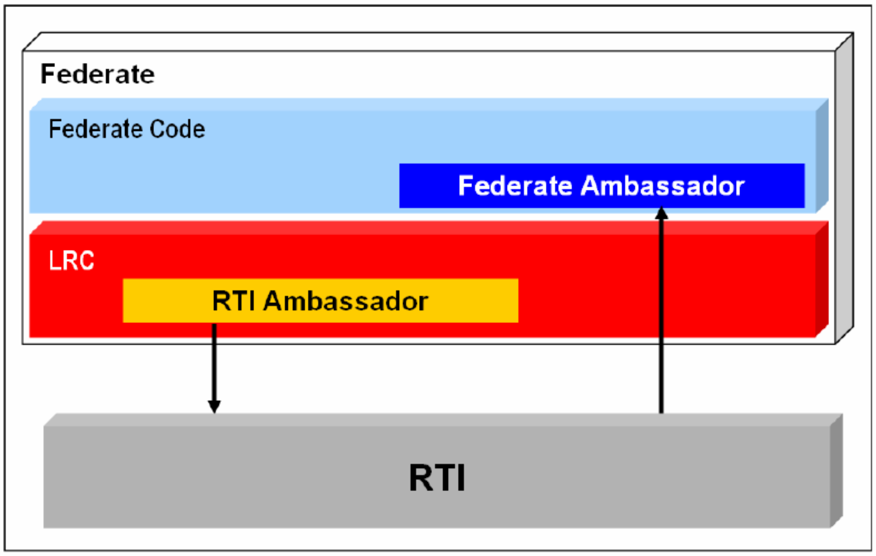


Figure 2-16: RTI and Federate Ambassador (DMSO, 1998)

The RTI is comprised of the following three components: the RTI Executive process (RtiExec), the Federation Executive process (FedExec), and the libRTI library. The FedExec manages the process of joining federates and resigning the federation and facilitates data exchange between participating federates. The RtiExec manages the creation and destruction of multiple federation executions within a network. The libRTI library extends RTI services to the federate developer. Data exchange between federates in a federation occurs only through the RTI by the HLA rules and is accomplished by means of the RTIambassador and FederateAmbassador. Judith et al (1998) explains that adopting the HLA standard in distributes simulation applications may reduce the cost and time required to develop new simulations as it promotes interoperability and reusability of legacy simulation models in order to develop a new and more complex simulations.

2.6.2 Distributed Simulation Applications

As computer hardware technology advances and the cost of computing decreases, the application areas in the business enterprise that can benefit from distributed simulation keeps growing. Also, a major reason for using distributed simulation applications is to reduce the length of time required to execute the simulation and/or to enable larger and more complex simulations to be executed by utilizing resources from multiple computers when a single computer may not support enough computing resources to perform the simulation (Fujimoto, 2000; Fujimoto, 2003).

Uygun (2009) explain that manufacturing processes have become extremely complex and that certain processes in the chain are performed from distributed environments leading to the need of more sophisticated integration and exchange of information in regard to the development and application of manufacturing simulations for decision-making. This particular need leads to Uygun (2009) description for using high level architecture (HLA) and its object model template (OMT) in order to develop distributed manufacturing simulations. One drawback explained by Uygun (2009) is that with HLA-based simulation systems it is not possible to model every manufacturing process scenario and that in certain instances an information translator or adaptor it's employed during implementation. Uygun (2009) describes "a distributed manufacturing simulation (DMS) as a manufacturing simulation that is composed of multiple software processes which are independently executed in different places but interacting with each other" (p. 1534).

Cho (2005) developed a distributed simulation approach with a time-driven mechanism that was used to simulate the occurrences of discrete events using distributed entities that replicate physical entities in the manufacturing shop floor. McGinnis et al (2006) used HLA to develop a distributed simulation of a 300 mm fabrication line and emphasized that appropriate synchronization techniques can significantly reduce simulation execution time.

Ramakrishnan and Wysk (2002) also developed a distributed simulation and control framework that used visual basic applications and HLA to define the integration mechanism of operational and strategic issues with a shop floor control system. Ramakrishnan (2008) developed the business process driven operations management (BP-DOM) framework for effective decision making in an enterprise or supply chain. The author emphasized that allowing users to manage the integration and functionalities of business processes and operational processes models in a single platform is a critical factor for the success of business enterprises in today's market. Ledermann et al (2001) used a distributed simulation to apply supply chain optimization approaches across globally distributed locations.

2.7 Gap Analysis

The literature review in this section presents the developments of MBSE methodologies in the Systems Engineering domain and its applications. In addition, it examined the literature for applications of system lifecycles or MBSE methodologies in the development of distributed and hybrid simulations for complex business systems. Our literature review reveals that “there is not an MBSE methodology based roadmap for the design and architecting of distributed and hybrid simulation systems”.

Distributed and Hybrid simulations systems can benefit from the application of MBSE methodologies as the methods inherent in these methodologies are based on systems engineering lifecycle models and system modeling languages. In general, minimal empirical work has been reported in the use of MBSE methodologies for the implementation of distributed and hybrid simulation systems. The following statements listed below exhibit issues with the lack of MBSE support in the developments of distributed and hybrid simulation systems:

- In general, the empirical work shown in the literature regarding distributed and hybrid simulation applications are more concern in their design and implementation and lack an integrated and systematic approach to initial analysis and functional requirements modeling as well as a holistic approach to the simulation lifecycle.
- Literature show that well-structured process modeling techniques that combine expressiveness, simplicity and formal semantics are being used in the implementation of hybrid simulation systems but the absence of standard business process modeling concepts present challenges in their use for system developments (Van der Aalst, 2004). As evidence by the literature review the adoption of MBSE methodologies in support for specification, design, integration, verification and validation of the system development lifecycle is potentially beneficial in distributed and hybrid simulation systems.

- Vergidis et al (2008) explained that the definition of hybrid modeling techniques that support performance analysis and enable process optimization will be beneficial. According to the author many business process modeling languages spend a lot of effort on describing business complexity through diagrammatic and semantic structures but lack support for the analysis and optimization of business process.
- One drawback explained by Uygun (2009) is that with HLA-based simulation systems it is not possible to model every manufacturing process scenario and that in certain instances an information translator or adaptor (middleware) it's employed during implementation. Lack of input and output modeling formalism with the use of middleware in distributes simulation applications presents a design and implementation challenge.
- Votintseva et al (2011) work explores the integration of the SysML modeling language and the ModelicaML simulation language to perform requirement evaluations and functional design scenario testing. However, Votintseva et al (2011) concludes that in large industrial projects the use of simulation for early system design evaluation might require different modeling languages and simulation methods (i.e., distributed and hybrid systems) due to increasing complexity of industrial system developments needed today.
- Brito et al (2011) expresses that what guarantees the advantages of using hybrid simulation applications are not the independent benefits of the simulation approaches, but the capacity of integration between the methodologies with the definition of a process of exchange of information and support.
- Russell (2012) argues that as system designs grow in complexity the need for more effective decision support mechanisms are more eminent in the development process.

2.7.1 Literature Review Gap Summary

Table – 2.2 exhibits the literature gap that exits in the definition of MBSE methodologies for a holistic lifecycle approach to distributed and hybrid simulation system developments. Distribute and hybrid simulation implementations have very seldom applied systems engineering lifecycle models and system modeling languages in their design and implementation efforts.

Table – 2.2: Literature Review GAP

Researcher's	**Distributed**	**Hybrid**				Modeling Languages	**MBSE Methods**
		Discrete-Event	System Dynamics	Agent-Based	Analytic		
Votintseva et al (2011)		x				x	x
Brito (2011)		x	x				
Uygun (2009)	x	x					
Cho (2005)	x	x					
Ramakrishnan (2008)	x	x					
Rabelo et al (2007)		x	x		x		
McGinnis (2006)	x	x					
Scholl and Phelan (2004)			x	x			
Lattila et al (2010)			x	x			
BenDor et al (2009)			x	x			
Lee and Kim (2002)					x		
Helal (2008)		x	x				
Rabelo et al (2003)		x	x				
Jaebok (2005)	x	x					
Stienman (1991)	x	x					
Fujii at al. (1999)	x	x					
Stienman (1992)	x	x					
Ramakrishnan and Wysk (2002)	x	x					
McGinnis et al (2006)	x	x				x	
McGinnis et al (2009)						x	
Wang and Dagli (2008)		x			x	x	
MBSE Approach to Distributed & Hybrid Simulations							
Pastrana (2013)	x	x	x	x	x	x	x

As we looked at the developments in the literature in regards to the application of MBSE methodologies research practitioners presented capabilities and advantages of using these methodologies in systems and product development efforts.

In Estefan (2008) survey of MBSE methodologies he notes that acknowledging the effect of PMTE elements in technology and people lead to the successful implementation of MBSE methodologies into large-scale development of complex systems within organizations. Market conditions and global business strategies are driving enterprises to adopt enterprise-wide system and product development strategies for conducting day-to-day business operations. Process, methods, tools and environmental factors in business dynamics today required the development of distributed and hybrid simulation systems for decision-support systems.

Votintseva et al (2011) discusses a model-based approach for systems simulation development efforts to synchronize early design phases for concept evaluation and functional design. This notion supports our belief that MBSE can help analysts and developers in the conceptualization efforts and definitions of interoperability characteristics and functional requirements needed for the successful implementation of distributed and hybrid simulation systems for business enterprises. Further, MBSE can allow simulation engineers to formally model different aspects of a problem ranging from architectures to corresponding behavioral analysis, to functional decompositions and user requirements (Jobe, 2008).

CHAPTER 3. RESEARCH METHODOLOGY

The literature review in the previous chapters identified the perceived gap of architecting the lifecycle of distributed and hybrid simulation systems. The current research proposes to develop a new methodological roadmap based on MBSE in order to fill this gap.

3.1 General Introduction to the Research Methodology

This research uses a pseudo hypothetico-deductive model of scientific research that works to develop a theory to account for knowledge gained by interviews, observations, and experimentation. The hypothetico-deductive research method starts with the recognition of a phenomenon. Relevant observations are then collected and analyzed in order to develop a statement of the research premises, directions and assumptions that are then operationalized and tested.

The current research is an exploratory type of research that sets the ground to further research the application of MBSE methodologies system lifecycle models for the implementation of distributed and hybrid simulation systems. The essence of the hypothetico-deductive is utilized within our view of the research process as described by Figure 3-1.

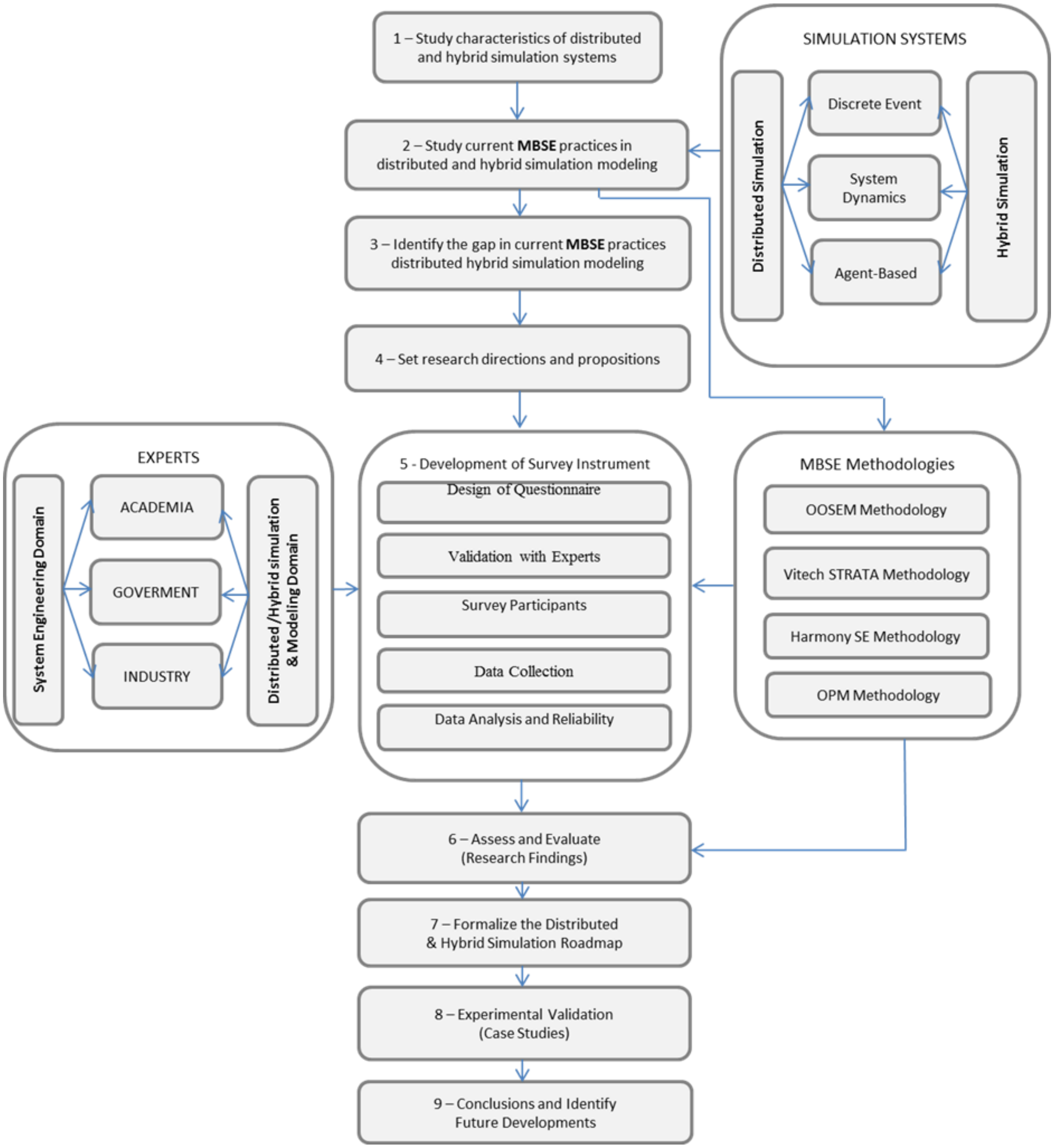


Figure 3-1: Research methodology

Our literature review in Chapter 2 identified literature gaps in terms of distributed and hybrid simulation systems developments. The research methodology will assess M&S expert experience in regards to the capabilities and benefits of MBSE methods and tools in distributed and hybrid simulation development efforts. Thus, a survey instrument will be constructed to conduct the MBSE methods and tools assessment. Survey participants from academia, industry and government will be invited to participate in our research study. Data collection and analysis will be performed to guide the simulation development roadmap. Chapter 5 introduces a case study that will be used for the definition, evaluation and experimentation of MBSE methodologies for architecting the lifecycle of distributed and hybrid simulation systems.

3.2 Literature and Initial Steps

The first four steps in the methodology have been covered in the first two chapters. The literature review explored that need and characterized it. The research premises and directions have been stated as follows:

1. Managers of the complex systems need new simulation tools that can accommodate the differences between levels in a holistic, enterprise-wide perspective. MBSE can allow simulation engineers to formally model different aspects of a problem ranging from architectures to corresponding behavioral analysis, to functional decompositions and user requirements (Jobe, 2008).
2. Current discrete and continuous simulation approaches; used separately, fall short in meeting the challenges created by integration in the business enterprise. Jahangirian (2010) review of simulation in manufacturing and business explains that distributed and hybrid simulation methods are becoming increasingly popular because of the current trend to provide an enterprise-wide solution. However, Uygun (2009) explains that the lack of input and output modeling formalism with the use of middleware in distributed simulation applications presents a design and implementation challenge

3. Literature show that well-structured process modeling techniques that combine expressiveness, simplicity and formal semantics are being used in the implementation of hybrid simulation systems but the absence of standard business process modeling concepts present challenges in their use for system developments (Van der Aalst, 2004).
4. There are not recognized methodologies to implement distributed and hybrid simulations. The current architecting processes are inadequate for meeting the needs of the lifecycle of a distributed and hybrid simulation system.
5. A survey of modeling and simulation practitioners will be conducted to gather their professional views, judgments and opinions regarding the capabilities and benefits of MBSE methods and tools for developing distributed and hybrid simulation systems according to their current and/or recent simulation development experience.

Simulation with no doubt is advantageous over other analytical techniques in modeling and analysis of complex systems. Moreover, the literature shows that simulation and modeling techniques have been applied in a wide-variety of business applications for decades. Yet the changes in the environment and perspectives created challenges to the traditional simulation techniques. Distributed and hybrid simulation system approaches offer several advantages over the use of either continuous or discrete simulation systems or techniques separately. As real life business operations and systems get more complex and larger distributed and hybrid simulation techniques implementation needs increase. Based on the previously stated premises, we have identified a gap in our research efforts that shows “there is not a recognized methodology or framework for the design and architecting of distributed and hybrid simulation systems”. Further, we believe the use of MBSE methods and tools can contribute present a formal and well-structured approach to modeling different aspects of a complex system ranging from architectures to corresponding behavioral analysis, to functional decompositions and user requirements as indicated by Jobe (2008). Our survey research methodology will give us some insight to the current capabilities and benefits of using MBSE methods and tools in current distributed and hybrid simulation development in the academic, industrial and government professional domains.

3.3 Development of Survey Instrument

In general, a survey can be defined as a structure way to collect information from respondents with the purpose of developing a concept or understanding of a particular subject in study. In simplest form, Tanur (1982) states that a survey means "gathering information about the characteristics, actions, or opinions of a large group of people, referred to as a population". In step 5 of our research methodology intentions are to collect the views, judgment and opinions of the current use, capabilities and benefits of MBSE methods and tools in the development of distributed and hybrid simulation systems by modeling and simulation professionals.

It was determine that these views, judgment and opinions of the capabilities and benefits of using MBSE methods and tools for distributed and hybrid simulation development will be best gathers by the use of a survey instrument. The survey instrument or questionnaire will be divided in several sections, called "constructs", that will collect the experiences from the modeling and simulation professionals with MBSE during their simulation system developments. The survey constructs and items are mainly driven by the literature finding identified in Chapter 2 regarding current MBSE methodologies. Further, a validation process will take place as we develop our survey questionnaire as to deem the most appropriate survey items with modeling and simulation professional from each of the academic, industrial and government domains of practice.

Experts from academia, government, and industry with a wide variety of complex system simulation developments experience will be sought as survey participants. The survey questionnaire instrument will be deployed electronically through an email invitation. Leads for email invitations for the modeling and simulation professionals were identified through the literature, research advisor recommendations, researcher's participations in modeling and simulation conferences and personal contacts. Survey Monkey (www.surveymonkey.com) will the online survey platform technology used on this research study efforts and methodology.

3.4 Research Findings and Roadmap Development

Survey respondent's data will be collected and analyzed. Steps 6 and 7 in our study demonstrates our methodological efforts which will assess the response data findings and aggregate values for the determined survey construct's and items to gather an understanding of the professional views, judgments and opinions of the simulation and modeling professionals regarding the capabilities and benefits of using MBSE methods and tools for distributed and hybrid simulation developments. The survey study findings will guide the development of a distributed and hybrid simulation system development roadmap.

MBSE methods and tools capabilities and benefits will be taken into considerations as we define our simulation development roadmap. Modeling and simulation professionals' developmental experience with MBSE methods and tools have not been documented in the literature up to date. MBSE modeling languages usage data from survey participants and their application at the requirement and architectural system design levels of the development life cycle can provide good insight in our roadmap development efforts. In addition, to what level it has benefited their business organization can provide further research directions and efforts.

3.5 Experimental Validation

It is important to validate (Step 8) the lessons learned from the previous steps and the formalized developmental roadmap. A couple of case studies will be used to validate our distributed and hybrid simulation developmental roadmap. The first case study presents a distributed and hybrid simulation approach to the Port Maritime Operations at the Port of Balboa (Republic of Panama). This particular case study is presented in Chapter 7 and follows the newly defined developmental roadmap to demonstrate and validate the roadmap process. The second case study is related to a military war fighting scenario and is presented in Chapter 8. With the use of our developmental roadmap adequate interoperability between the different simulation models is implemented and demonstrated in the two case studies.

3.6 Conclusions and Further Developments

In this part (Step 9), we will in abbreviated form present our findings. The developed roadmap will be explained in detailed. In addition, we will discuss the broader implications of the different conclusions. A very important aspect is to review the limitations of this research. It is important to analyze the weaknesses and offer suggestions for future research. It is required to mention the different contributions to the body knowledge achieved during the time of study.

CHAPTER 4. SURVEY DESIGN

4.1 Introduction

This chapter will describe the methods and procedures used to accomplish our survey study. Our main goal with the survey study is to collect modeling and simulation (M&S) expert views, judgments and opinions regarding the capabilities and benefits of MBSE methods and tools for developing distributed and hybrid simulation systems. These expert views, judgments and opinions will be collected through an online self-administered survey instrument. The remainder of this chapter will describe in detail survey participants, survey development and survey research aim.

4.2 Survey Participants

Sampling for systems engineering and distributed/hybrid simulation experts was done through email invitations. Experts from academia, government, and industry with a wide variety of complex system simulation developments experience were sought as survey participants. The selection of companies and organizations to be invited for survey participation was guided by the researcher's knowledge about the business entities. Complex systems development projects by the participating companies and organizations that would require distributed and hybrid simulation systems for analysis or training range from defense and aerospace systems manufacturer's (e.g., General Dynamics, Lockheed Martin, Thales Group, etc.) to complex business process simulation (manufacturing, port & harbor logistics, warehousing, healthcare, airports, advance analytics, etc.) practitioners like AnyLogic, Simul8, Simio and the like.

Academic institutions professionals in the field of modeling and simulation with systems engineering experience were also seek as survey participants. Leads for email invitations for these academic professionals were identified through the literature, research advisor recommendations, researcher's participations in modeling and simulation conferences and personal contacts. Approximately 100 survey invitations were sent. The invitations included an informed consent in which participants were presented with the research topic, principal investigator information, academic institution, link to the online survey, instructions and all required contact information for any questions or concerns. Participants were indicated that their participation is voluntary and they could terminate their survey participation at any time during the process.

4.3 Survey Development

MBSE methodologies provide a process description, modeling languages and tools that can support the development of distributed and hybrid simulation systems throughout the entire project lifecycle. Our survey instrument development aims at capturing the experiences of modeling and simulation professionals with MBSE methods and tools. Companies and organizations which core business practices include manufacturing and integration of complex systems use MBSE methods and tools in their development. The experiences of these organizations are essential to our survey study because their adoption of MBSE methods and tools during their complex system development support industry standards development and the associated standard development organizations. The "Object Management Group" (OMG - www.omg.org) is an international non-profit technology standards consortium that moderates the development of MBSE languages (e.g., UML, SysML, BPMN, etc.) and system modeling standards. Their efforts include the support of OMG standard developments as well as support for software tool vendors, end-users, academic institutions and different government organization worldwide.

Whittle et al (2009) defined a survey to study the efficacy of model driven engineering (MDE) methods and tools. The survey study is part of a project called "Empirical Assessment of Model Driven Engineering" (EA-MDE) led by Lancaster University, UK. He explains that the survey study was aimed and designed to capture system development practitioners experiences that surround the domain of MDE efforts like model-based engineering (MBE), model driven architecture (MDA), model-based systems engineering (MBSE), and other system modeling practices involving domain specific languages (DSL) and domain specific modeling languages (DSML) methods and tools. Further, Whittle et al (2009) explains that the EA-MDE survey study is aimed at understanding what factors have a positive or negative effect in the adoption of MDE practices for the industrial MDE community. He discusses that particular knowledge exists in the industrial MDE practitioners since they deploy MDE based modeling tools and processes in real industrial projects with actual financial performance requirements and deadlines. Our survey development efforts will adapt some of the survey items developed by Whittle et al (2009) to fit the scope of our MBSE methodological framework development and research study.

4.3.1 General Survey Arrangement

The general arrangement of our survey instrument includes an initial section that will collect information regarding what type of MBSE methods and tools the modeling and simulation professionals are actively using or have used during their recent systems developments. As we have discussed in our literature review in Chapter 2 a number of MBSE methodologies employ specific modeling software tools and adopt particular system modeling languages. We are also interested in knowing which system modeling languages are being used by distributed and hybrid simulation modelers and practitioners in industry. Following this initial inquiry we will present the main constructs with their particular items that will guide our framework development. Finally, a number of general inquiries regarding the industry and experience of the survey participants will be presented in the survey process to collect domain specific information of the modeling and simulation professionals.

4.3.2 Survey Constructs and Items

The survey constructs and items are mainly driven by the literature finding identified in Chapter 2 regarding current MBSE methodologies. Moreover, Whittle et al (2009) EA-MDE survey questionnaire instrument was studied to guide us in our survey instrument constructs and items selection. The selection of our survey instrument constructs and items in support of our MBSE approach to distributed and hybrid simulation systems are shown Table 4-1.

Grady (2008) described MBSE methodologies as the formalized application of modeling principles, methods, languages, and tools to the entire lifecycle of large, complex, interdisciplinary and sociotechnical systems. One of the major characteristics of MBSE methodologies is the use of modeling languages (i.e., UML, SysML, SDL, EFFBD and OPDs/OPL) and tools with data and model management applications that support interdisciplinary system development collaboration efforts.

Table 4-1: MBSE Approach to Distributed and Hybrid Simulation Systems Survey Constructs & Items

Constructs	Items
MBSE Requirements Methods/Tools Capabilities	Successful definition of requirements Communication with different Stakeholders Management and Traceability Trade-off Analysis
MBSE Requirements Methods/Tools Benefits	Personal Productivity Development Team Productivity Easier maintenance of M&S project requirements Overall project implementation and validation
MBSE Systems Architectural and Design Methods/Tools Capabilities	Auto-generation of System modeling diagrams Auto-generation of architecture/design documentation Executable architectures and design models Code generation capabilities
MBSE Systems Architectural and Design Methods/Tools Benefits	Personal Productivity Development Team Productivity Easier maintenance of M&S Architectures and Designs Overall project implementation and validation
Overall MBSE Organizational Benefits	Support M&S projects through entire development lifecycle Organizational agility and new business opportunities

Whittle et al (2009) notes that their MDE survey findings should not be considered as a homogeneous group view and opinion. Furthermore, he indicates that differences in the MDE practitioner communities should be recognized. As noted, we are particularly interested in collecting the views, judgment and opinions of the distributed and hybrid simulation system developers and modelers with systems engineering experience. The researcher has selected companies and organizations that fit the scope of our research study.

4.3.3 Items Scale and Measurement

A 5-point likert scale was selected for our survey instrument. DeVellis (2003) notes that there are a couple of particular benefits of using a five point likert scale. These benefits are that it enables the measurement of variability and it also helps survey participants to differentiate in a meaningful way between items alternatives with a finite distinction and neutral response as well. The 5 – point likert scale intended for use in our research instrument is as follows:

_ (Strongly Disagree) _ (Disagree) _ (Neutral) _ (Agree) _ (Strongly Agree)

4.4 Survey Research Aim

In our simulation development roadmap definition we are particularly interested in MBSE capabilities for defining system requirements and to understand how beneficial are MBSE methods and tools in developments of system models and architectural designs. The results of our survey instrument will guide us in our simulation development roadmap definition efforts for an MBSE approach to distributed and hybrid simulation systems developments.

The survey instrument will collect information regarding the capabilities and benefits of MBSE methods and tools in distributed and hybrid simulation developments. Different MBSE methodologies as discussed in Chapter 2 include different capabilities and benefits in the definition of system requirements and architectural design implementation efforts. Garcia (2008) describes Model-Based System Engineering as “the practice and discipline within the field of system engineering that models system interactions and interoperability in order to better engineer or develop an intended system design” (p. 63). System interactions and interoperability characteristics are essential in the definition and implementation of distributed and hybrid simulation systems. These characteristics should to be taken into consideration throughout the entire system development cycle.

CHAPTER 5. DATA COLLECTION AND ANALYSIS

5.1 Introduction

The data collection and results analysis will be presented in this chapter. Survey distribution was conducted as indicated in Section 4.2. Over a 100 invitations were sent to modeling and simulation experts from academia, government, and industry with a wide variety of complex system simulation developments experience. A total of 62 participants were recorded by the "Survey Monkey" online survey platform. Survey participation was voluntary and each participant could terminate survey at any time. Our data collection process indicated that 67.74% of respondents completed the survey in its entirety. This meant that for data analysis purposes a data set representing 42 participant response data was analyzed. Further, data collected provided a pragmatic information level from modeling and simulation professionals to garner a better understanding of MBSE methods and tools usage and to what level it benefited their business organization. Descriptive statistics and validation of survey constructs are included in the analysis discussions.

5.2 Analysis of Participants Demographics

Participant's demographics were collected during our survey study. No personal identifiable information was collected. This section will present the participants demographic information collected. The exact survey instrument can be found in Appendix A. The demographic information was mainly related to their level of experience, their organization type, to what extent the organization has adopted the MBSE practice and their MBSE roles during systems developments.

First participant's demographic type of questions was related to the years of experience. Data collected from Questions #13 indicates that 85.7% of the survey participants have at least 5 years of experience in modeling and simulation systems development. In addition, more than 60% of participants have at least 10 year of experience. Table 5.1 summarizes Question #13 response data.

Table 5-1: Question #13 Response Data

About how long have you been involved in Modeling and Simulation systems development?		
Answer Options	**Response Percent**	**Response Count**
0-5 years	14.3%	6
5-10 years	26.2%	11
10-15 years	26.2%	11
15-20 years	23.8%	10
>20 years	9.5%	4
Total		**42**

The study data related to the years of experience of survey participants indicated that the large majority of the modeling and simulation professionals have a significant level of experience. Now, data collected in Question #14 was related to the participant's current systems development role in modeling and simulation projects. In large complex system developments projects a systems engineer collaboration can take on a number of roles which could range from developer, modeler, architects, etc. based on your technical trade and previous experience in project developments. Regardless of your particular systems development role systems engineers are involved in the requirement definition process to some level throughout the entire development lifecycle.

Table 5-2: Question #14 Response Data

Which of the following best describes your current systems development role in M&S projects?		
Answer Options	**Response Percent**	**Response Count**
Systems Engineer	33.3%	14
Systems Developer	4.8%	2
Systems Modeler	4.8%	2
Systems Architect	19.0%	8
Team Leader	16.7%	7
Project Manager	14.3%	6
Domain Expert - Specialist	2.4%	1
Systems Testing	2.4%	1
Systems Validation	2.4%	1
Any comment/opinion regarding this question?		5
Total		**42**

The response data for Questions #14 indicates a majority of participants in the role of "Systems Engineer" a 33% response rate. The systems architects, team leaders and project manager roles in the collected data represent a 50% of the survey respondents which can be interpret as the more experience modeling and simulation professionals. The "Systems Architects" is the second largest percent of respondents modeling and simulation systems development role. This particular systems development role can support our research study goals. This is due to the fact that "Systems Architects" will certainly understand the capabilities and benefits of MBSE methods and tools during systems developments. It can be said that systems architects, team leaders and managers are required to have more in depth domain knowledge and can contribute to the integration and validation phases of the systems development processes. These findings have significant impact in our research efforts as "Systems Engineers", "Systems Architects", "Team Leaders" and "Project Managers" represent more than 80% of the survey respondents.

Table 5-3: Question #15 Response Data

How long have you been in your current systems development role?		
Answer Options	**Response Percent**	**Response Count**
1-2 years	21.4%	9
2-5 years	28.6%	12
5-10 years	28.6%	12
10-15 years	9.5%	4
>15 years	11.9%	5
Total		**42**

Responses for Question #15 describe the amount of experience the respondents have in their current systems development roles. The response data indicates that over 50% of participants have significant experience in their current roles. Again, this contributes to the reliability and validity of the responses and data representation collected in regards to the capabilities and benefits of MBSE methods and tools for the development of distributed and hybrid simulation systems efforts.

Table 5-4: Question #16 Response Data

Which of the following best describes your organization?		
Answer Options	**Response Percent**	**Response Count**
Academic	21.4%	9
Industry	54.8%	23
Government	23.8%	10
Total		**42**

Question #16 described the percent of survey participants from academia, government, and industry. A wide variety of complex system simulation developments experience was sought as survey participants to include the views, judgment and opinions different organizations for the capabilities and benefits of MBSE development efforts. Academia, government and industrial entities are managed by different business operational and financial benefits. It was expected that a higher percentage of industrial modeling and simulation professionals were going to participate in the survey. Interestingly, the academic and government M&S professionals were almost equally represented by the collected data.

Table 5-5: Question #17 Response Data

Which of the following best describes the principal industry of your organization?		
Answer Options	**Response Percent**	**Response Count**
Aerospace	23.8%	10
Defense	64.3%	27
Automotive	0.0%	0
Finance & Financial Services	0.0%	0
Manufacturing	0.0%	0
Telecommunications	0.0%	0
Energy	0.0%	0
Space Systems	4.8%	2
Other	7.1%	3
Other (please specify)		6
Total		**42**

Data collected from Question #17 describes the principal industries where the modeling and simulation experts implement and use MBSE methods and tools for systems developments. The majority of the survey participant's principal industry of practice is "Defense" with over 60%. This finding is not a surprise as the majority of the MBSE practitioner's as represented by responses from Question #16 are from industrial type organizations. As discussed in the previous section we mentioned that large complex systems development projects that would require distributed and hybrid simulation systems for analysis or training are typically from defense and aerospace systems manufacturer's (e.g., General Dynamics, Lockheed Martin, Thales Group, etc.). Thus, the second largest industry practice represented by this data is from the "Aerospace" industry with approximately 24%.

Table 5-6: Question #18 Response Data

Approximately how many employees are there in your company or organization?		
Answer Options	**Response Percent**	**Response Count**
1 -10	4.8%	2
10 -100	11.9%	5
100 -1000	21.4%	9
1000 - 10000	19.0%	8
> 10000	42.9%	18
Total		**42**

Another demographic response data collected from Question #18 was the number of employees in the companies and/or organizations represented by the survey participant's which conduct MBSE development activities. Data in this question indicates that approximately 43% of modeling and simulation professional using MBSE methods and tools are represented by organizations with more than 10,000 employees. In addition, the large majority of respondents (over 60%) work in organizations that have at least 1,000 employees.

Table 5-7: Question #19 Response Data

In which areas of system development have your organization use MBSE languages, methods and tools for Modeling & Simulation projects? Check all that apply and specify other.		
Answer Options	**Response Percent**	**Response Count**
Requirements Management	83.3%	35
System Design	88.1%	37
System Validation	42.9%	18
Executable Models / Simulation	47.6%	20
Verification Planning / Test Execution	45.2%	19
Trade-off Studies	21.4%	9
Code Generation	54.8%	23
Other	7.1%	3
Other (please specify)		3
Total		**42**

The last demographic type of data collected was described by Question #19. As noted in our literature review, Jobe (2008) maintains that MBSE can allow simulation engineers to formally model different aspects of a problem ranging from architectures to corresponding behavioral analysis, functional decompositions and user requirements. Our simulation development roadmap definition is particularly focus in the initial requirement analysis and the architectural system design concepts of distributed and hybrid simulation systems developments with MBSE concepts. Russell (2012) argues that as system designs grow in complexity the need for more effective decision support mechanisms are more eminent in the development process. Data findings included in Question #19 supports the notion presented by Russell (2012) as over 80% of respondent organizations represented in our survey study use MBSE methods and tools for “Requirement Management” and “System Designs” developments and over 60% have at least 1,000 employees. Highly complex systems designs and system integrations are usually carried out by large organizations with defense and aerospace systems manufacturing capabilities (e.g., General Dynamics, Lockheed Martin, Thales Group, etc.). These types of organizations are well represented in our response data as noted in Question #17. In general, it can be stated that the demographic response data included in our survey study can support our survey constructs and items analysis and overall findings related to MBSE methods and approaches to distributed and hybrid simulation systems developments.

5.3 Survey Constructs and Items Data Analysis

The survey constructs presented in the Chapter 4 detailed the capabilities and benefits MBSE methods and tools provide to system development efforts in terms of requirement management and systems architectural design. Based on our literature review in Chapter 2 and supporting literature survey of leading MBSE methodologies and their respective tool capabilities presented by Estefan (2008) our survey constructs and items (or variables) were identified. Furthermore, our survey development efforts adapted some of the survey items developed by Whittle et al (2009) to fit the scope of our MBSE simulation development roadmap and research study. In addition, Whittle et al (2009) notes that their MDE survey findings should not be considered as a homogeneous group view and opinion. Furthermore, he indicates that differences in the MDE practitioner communities should be recognized. Thus, we are particularly interested in collecting the views, judgment and opinions of the distributed and hybrid simulation system developers and modelers with systems engineering experience.

5.3.1 MBSE Survey – Construct #1

The items or variables that comprise Construct #1 aim at gathering the experiences of modeling and simulation professionals with requirement management capabilities of MBSE methods and tools during M&S project developments. Question #3 response data describes the level of agreement expressed by survey participants regarding the contribution of MBSE languages to the successful definition of systems requirements in M&S project developments. As shown in Table 5.8, a level of agreement over 75% was found.

Table 5-8: Question #3 Response Data

From your experience, to what level would you agree or disagree that MBSE languages (e.g., UML, SysML, IDEF0, etc.) contribute to the successful definition of system requirements of your M&S project?

Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Total**
Count	0	3	8	30	8	49
Percentage	0.0%	6.1%	16.3%	61.2%	16.3%	100
Any comment/opinion regarding this question?						9

Question #4 response data found that a majority (over 60%) of modeling and simulation professionals which participated in our study agreed that MBSE languages are capable of successfully communicating systems requirements to clients and other M&S development team members. Questions #1 and #2 collects demographic information regarding MBSE methods, tools and languages that are in used by M&S professionals in the academic, industrial and government community of practice.

Table 5-9: Question #4 Response Data

From your experience, to what level would you agree or disagree that MBSE languages (e.g., UML, SysML, IDEF0, etc.) contribute to the successful communication of system requirements to the client and other team members in your M&S project?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Totals**
Response Count	0	5	9	23	12	49
Percentage	0.0%	10.2%	18.4%	46.9%	24.5%	100%
Any comment/opinion regarding this question?						9

Table 5.9 demonstrates that over 60% of respondents agreed with the notion that MBSE requirement and management tools are capable of supporting the successful definition of M&S project requirements. Demographic finding from survey participants can support the findings of this question as over 80% of participants reported their companies and organizations actively use MBSE method and tools in M&S systems developments.

Table 5-10: Question #5 Response Data

From your experience, to what level would you agree or disagree that MBSE tools with requirements definition and management (e.g., traceability) capabilities contribute to the successful communication of system requirement to the client and other team members in your M&S project?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count**
Response Count	0	3	8	26	12	49
Percentage	0.0%	6.1%	16.3%	53.1%	24.5%	100%
Any comment/opinion regarding this question?						6

Data response for Question #6 describe MBSE “trade-off analysis” among M&S professional was not necessarily satisfactory. The large majority (over 60%) of MBSE practitioners do not feel that “trade-off analysis” contributes to the successful definition and communication of systems requirement among team members and to the client.

Table 5-11: Question #6 Response Data

From your experience, to what level would you agree or disagree that MBSE tools with requirements trade-off analysis capabilities contribute to the successful communication of system requirement to the client and other team members in your M&S project?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count**
Response Count	0	2	28	15	4	49
Percentage	0.0%	4.1%	57.1%	30.6%	8.2%	100%
Any comment/opinion regarding this question?						4

5.3.2 MBSE Survey – Construct #2

Items or variables described in Construct #2 are intended to assess the benefits of using MBSE methods and tools by distributed and hybrid simulation systems practitioner’s at different levels. First, we wanted to know if MBSE methods and tools increase the personal productivity of practitioners. The response data indicated that 69% of respondents agreed that MBSE requirement management type methods and tools increased their personal productivity.

Table 5-12: Question #7 Response Data

During your recent modeling and simulation projects to what level would you agree/disagree that MBSE system modeling methods and tools have:						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count (%)**
Increased your personal productivity	0	4	11	26	8	49
	0.0%	8.2%	22.4%	53.1%	16.3%	100%
Increased the productivity of the development team	0	4	8	30	7	49
	0.0%	8.2%	16.3%	61.2%	14.3%	100%
Made it easier to define and maintain your M&S projects	0	3	10	27	9	49
requirements	0.0%	6.1%	20.4%	55.1%	18.4%	100%
Contribute to the overall project successful implementation	0	4	6	28	11	49
and validation of the system requirement process	0.0%	8.2%	12.2%	57.1%	22.4%	100%
Any comment/opinion regarding this question?						5

In addition, over 70% of M&S professionals that participated in the survey indicated that MBSE requirement management methods and tools even increased the productivity of the development team. Subsequently, M&S practitioners expressed that MBSE methods and tools made it easier to define and maintain their M&S project requirements in their companies and organizations. Also, over 70% of respondents agreed that MBSE methods and tools contributed to the overall M&S project successful implementation and validation of the systems requirement process.

5.3.3 MBSE Survey – Construct #3

Construct #3 items response data describes the experiences of modeling and simulation professionals with MBSE methods and tools automatic generation of system modeling diagrams capabilities for system architectural and design definition of M&S project developments.

Question #8 response data describes the level of agreement expressed by survey participants regarding the contribution of automatic generation of system modeling diagrams capabilities of MBSE tools to the successful definition of system designs and functional architectures in M&S project developments. As shown in Table #, a level of agreement 66% was found.

Table 5-13: Question #8 Response Data

From your experience, to what level would you agree/disagree that MBSE tools for automatic generation of system modeling diagrams (e.g., use case diagrams, activity, sequence, etc.) have or could have contributed to the successful definition of system design and functional architecture of your M&S project?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count**
Response Count	0	2	12	20	8	42
Percentage	0.0%	4.8%	28.6%	47.6%	19.0%	100%
Any comment/opinion regarding this question?						6

Question #9 response data found that a majority (over 60%) of modeling and simulation professionals agreed that automatic generation of architectural and design documentation capabilities of MBSE tools contributed to the successful definition of system designs and functional architectures in M&S project developments. Table 5.14 shows the response count and percentages for all the available responses provided to the respondents.

Table 5-14: Question #9 Response Data

From your experience, to what level would you agree/disagree that MBSE tools for automatic generation of architectural and design documentation have or could have contributed to the successful definition of the system architecture and design (i.e., functional, physical, and/or behavioral architecture) of your M&S project?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count**
Response Count	0	3	11	20	8	42
Percentage	0.0%	7.1%	26.2%	47.6%	19.0%	100%
Any comment/opinion regarding this question?						4

Table 5.15 establishes that over 70% of respondents agreed with the view that executable simulation capabilities of MBSE models contributed to the successful definition and implementation of M&S project's system architectures and design. MBSE methods and tools can allow simulation engineers to formally model different aspects of a problem ranging from architectures to corresponding behavioral analysis, to functional decompositions and user requirements (Jobe, 2008). Our response data findings assert that MBSE methods and tools are suitable the successfully implementation of M&S projects in industry.

Table 5-15: Question #10 Response Data

From your experience, to what level would you agree/disagree that MBSE tools with an executable simulation capability have or could have contributed to the successful definition and implementation the system architecture and design (i.e., functional, physical, and/or behavioral architecture) of your M&S project?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count (%)**
Response Count	0	1	10	23	8	42
Percentage	0.0%	2.4%	23.8%	54.8%	19.0%	100%
Any comment/opinion regarding this question?						2

Data response for MBSE "code generation" tools among M&S professional did not gain a significant majority agreement. Regardless, 59% of distributed and hybrid simulation practitioners found MBSE “code generation” methods and tools to contribute to the evaluation and/or testing of systems architectures and designs of M&S project developments. Table 5.16 shows the response count and percentages for all the available responses provided to the respondents.

Table 5-16: Question #11 Response Data

From your experience, to what level would you agree/disagree that MBSE software programming language code generation tools (e.g., C, C++, Java, etc.) have or could have contributed to evaluation and/or testing of the system architecture and design (i.e., functional, physical, and/or behavioral architecture) of your M&S project?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count (%)**
Response Count	0	7	10	18	7	42
Percentage	0.0%	16.7%	23.8%	42.9%	16.7%	100%
Any comment/opinion regarding this question?						4

5.3.4 MBSE Survey – Construct #4

Construct #4 are intended to assess the benefits of automation capabilities (e.g., code generation, automated documentation generation, and executable simulation) for system architecture and design using MBSE methods and tools by distributed and hybrid simulation practitioner’s at different levels. The first item in this construct wanted to assess if automation capabilities of MBSE methods and tools increase the personal productivity of practitioners. The response data indicated that 71% of respondents agreed that automation capabilities of MBSE methods and tools increased their personal productivity.

Table 5-17: Question #12 Response Data

During your recent modeling and simulation projects to what level would you agree/disagree that MBSE with automation capabilities (e.g., code generation, automated documentation generation, and executable simulation) for system architecture and design (i.e., functional, physical, and/or behavioral architecture) have or could have:						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count (%)**
Increased your personal productivity	0	4	8	21	9	42
	0.0%	9.5%	19.0%	50.0%	21.4%	100%
Increased the productivity of the development team	0	5	7	22	8	42
	0.0%	11.9%	16.7%	52.4%	19.0%	100%
Made it easier to define and develop your M&S system architecture and design	0	2	11	22	7	42
	0.0%	4.8%	26.2%	52.4%	16.7%	100%
Contribute to the overall project successful implementation and validation of the system architecture and design	0	3	10	21	8	42
	0.0%	7.1%	23.8%	50.0%	19.0%	100%
Any comment/opinion regarding this question?						4

In addition, over 70% of M&S professionals that participated in the survey indicated that automation capabilities (e.g., code generation, automated documentation generation, and executable simulation) for system architecture and design using MBSE methods and tools even increased the productivity of the development team. Further, 68% of M&S practitioners respondents expressed that automation capabilities of MBSE methods and tools made it easier to define and develop their M&S project's system architectures and designs. In addition, over 60% of respondents agreed that MBSE methods and tools contributed to the overall M&S project successful implementation and validation of the systems requirement process. Table # shows the response count and percentages for all the available responses provided to the respondents.

5.3.5 MBSE Survey – Construct #5

Construct #5 items response data are intended to assess the overall MBSE "Organizational Benefits" perceived by distributed and hybrid simulation practitioners. Question #20 response data describes the level of agreement expressed by survey participants regarding the contribution of MBSE languages, method and tools to support and maintain M&S projects throughout the entire development lifecycle. As shown in Table #, an agreement level of 86% was found.

Table 5-18: Question #20 Response Data

From your experience, to what level would you agree/disagree that MBSE languages, method and tools have or could have help your Organization to support and maintain M&S projects throughout the entire development lifecycle?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count (%)**
Response Count	0	1	5	28	8	42
Percentage	0.0%	2.4%	11.9%	66.7%	19.0%	100%
Any comment/opinion regarding this question?						1

Question #21 response data demonstrates the level of agreement expressed by survey participants regarding the contribution of MBSE languages, method and tools to respond faster to new client implementation requirements and/or business opportunities. As shown in Table #, an agreement level of 79% was found.

Table 5-19: Question #21 Response Data

From your experience, to what level would you agree/disagree that MBSE languages, method and tools have or could have help your Organization to respond faster to new client implementation requirements and/or business opportunities?						
Answer Options	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Response Count (%)**
Response Count	0	2	7	25	8	42
Percentage	0.0%	4.8%	16.7%	59.5%	19.0%	100%
Any comment/opinion regarding this question?						4

5.4 Survey Items Reliability Analysis

Survey reliability measure is related to the internal consistency of the questionnaire instrument. Tavakol et al (2011) explains that the alpha coefficient measure was developed by Lee Cronbach in 1951 in order to provide a measure internal consistency of test scales. In this section we present an internal consistency analysis of the response data provided by M&S experts with distributed and hybrid simulation system development experience. The analysis will be divided by constructs to present internal consistency adequacy of the overall research study findings. Further, descriptive statistics for each of the construct items will be provided to present mean and standard deviation details of the response data. All internal consistency "Cronbach's Alpha" computation and descriptive statistics were conducted using the Minitab version 16.1.

Construct #1 aimed at gathering the experiences of modeling and simulation professionals with requirement management capabilities of MBSE methods and tools during M&S project developments. The total internal consistency of the overall items response data for construct #1 was calculated to be 0.6661. Table 5.20 provides mean and standard deviation values as well as individual alpha values for each item.

Table 5-20: Construct #1 Reliability and Descriptive Statistics

Items	Mean	Std. Dev.	Cronbach's
Successful definition of requirements	3.919	0.722	0.5582
Communication with different Stakeholders	3.919	0.928	0.5582
Management and Traceability	3.946	0.848	0.6430
Trade-off Analysis	3.486	0.731	0.6113

Response data of construct #2 items were intended to assess the benefits of using MBSE methods and tools by distributed and hybrid simulation systems practitioner's at different levels. The total internal consistency of the overall items response data for construct #2 was calculated to be 0.7019. Table 5.21 provides mean and standard deviation values as well as individual alpha values for each item.

Table 5-21: Construct #2 Reliability and Descriptive Statistics

Items	Mean	Std. Dev.	Cronbach's
Personal Productivity	3.757	0.830	0.6582
Development Team Productivity	3.757	0.760	0.6377
Easier maintenance of M&S project requirements	3.865	0.787	0.6703
Overall project implementation and validation	3.973	0.866	0.5793

Construct #3 items response data described the experiences of modeling and simulation professionals with MBSE methods and tools automatic generation of system modeling diagrams capabilities for system architectural and design definition of M&S project developments. The total internal consistency of the overall items response data for construct #3 was calculated to be 0.7344. Table 5.22 provides mean and standard deviation values as well as individual alpha values for each item.

Table 5-22: Construct #3 Reliability and Descriptive Statistics

Items	Mean	Std. Dev.	Cronbach's
Auto-generation of System modeling diagrams	3.811	0.811	0.6225
Auto-generation of architecture/design documenation	3.757	0.830	0.6368
Executable architectures and design models	3.973	0.726	0.7252
Code generation capabilities	3.703	0.939	0.7044

Response data collected in construct #4 was intended to assess the benefits of automation capabilities (e.g., code generation, automated documentation generation, and executable simulation) for system architecture and design using MBSE methods and tools by distributed and hybrid simulation practitioner's at different levels. The total internal consistency of the overall items response data for construct #4 was calculated to be 0.7344. Table 5.23 provides mean and standard deviation values as well as individual alpha values for each item.

Table 5-23: Construct #4 Reliability and Descriptive Statistics

Items	Mean	Std. Dev.	Cronbach's
Personal Productivity	3.838	0.866	0.7514
Development Team Productivity	3.784	0.886	0.7561
Easier maintenance of M&S Architectures and Designs	3.811	0.739	0.8423
Overall project implementation and validation	3.784	0.787	0.8649

Construct #5 response data was intended to assess the overall MBSE "Organizational Benefits" perceived by distributed and hybrid simulation practitioners. The total internal consistency of the overall items response data for construct #5 was calculated to be 0.7242. Table 5.24 provides mean and standard deviation values as well as individual alpha values for each item. The minimum number of factors or items to compute alpha values for internal consistency evaluation is two factors. However, individual alpha values can be computed when you have at least a three factor analysis.

Table 5-24: Construct #5 Reliability and Descriptive Statistics

Items	Mean	Std. Dev.	Cronbach's
Support M&S projects through entire development lifecycle	4.0000	0.6667	0.7242
Organizational agility and new business opportunities	3.9189	0.7951	--

5.5 Overall Survey Finding Summary

All survey constructs internal consistency values were acceptable. These values provide a significant level of internal consistency and homogeneity amongst the survey constructs analyzed in this study. All individual constructs were found to be with in an acceptable level of reliability or internal consistency ranging from alpha values between 0.6 and 0.8. Tavakol et al (2011) notes that low values of alpha (< 0.50) could be poor interrelatedness of constructs items and higher values of alpha (> 0.90) can be due to redundancy issues with high number of items per construct. Thus, our computed alpha values suggest that the intended purpose of our survey constructs were found to be acceptable and provide an adequate level of support to our research study goals.

CHAPTER 6. ROADMAP FOR DEVELOPMENTS OF DISTRIBUTED AND HYBRID SIMULATION SYSTEMS

6.1 Introduction

This chapter presents guidelines for the development of distributed and hybrid simulation systems in respect to MBSE methods and tools used by academic, industry and government M&S experts. The guidelines are presented in the form of a roadmap description that spells out the recommended steps for architecting distributed and hybrid simulation systems. Our goal is to take into consideration the views, judgment and opinions of M&S experts regarding the capabilities and benefits of MBSE methods and tools for developing distributed and hybrid simulation systems. Ultimately, this chapter will introduced a well-structured process and MBSE based modeling techniques that will allow proper architecting, functional decomposition and users requirement definitions in support of the lifecycle management and implementation of distributed and hybrid simulation systems.

6.2 Roadmap Justification

The distributed and hybrid simulation domain practice acknowledges that a common or agreed simulation object or entity concept should be defined for proper simulation interoperability performance and implementation. A single or individual simulation approach to the ever increasing complexity of business enterprise processes today cannot be captured or analyzed by a single simulation and modeling paradigm. Not only capturing and modeling business process complexities for decision making is important. But understanding and managing the lifecycle of an entire distributed and hybrid simulation system design and implementation from cradle to grave is a challenge and should be of great importance as well.

MBSE can allow simulation engineers to formally model different aspects of a problem ranging from architectures, to corresponding behavioral analysis, to functional decompositions and user requirements (Jobe, 2008). Further, Van der Aalst, (2004) explained that the used of system engineering modeling languages can support a well-structured process or modeling techniques to provide the right level of expressiveness, simplicity and formal semantics required for the implementation of hybrid simulation systems; but the absence of standard business process modeling concepts present challenges in their use for system developments. Robinson (2008a) notes that "conceptual modeling is probably the most important aspect of a simulation study" (p.278) and expands on the notion that defining methods and procedures for it "is more of an 'art' than a science" (p.278) and that it is really a practice that is learnt largely by experience. These identified shortcomings in the literature are some of the principal motivators for our research study and the proposition of a roadmap for proper architecting of distributed and hybrid simulation systems.

6.3 Roadmap Overview

The conceptualized roadmap will support simulation practitioners with step-by-step guidelines for the development of distributed and hybrid simulation systems. The roadmap description will emphasize on conceptual modeling and interoperability characteristics for the successful development of system requirements and design concepts of distributed and hybrid simulation development throughout their entire system lifecycle. The MBSE based modeling techniques will allow proper architecting, functional decomposition and users requirement definitions in support of the lifecycle management and implementation of distributed and hybrid simulation systems. Figure 6-1 presents the general overview of the simulation development roadmap.

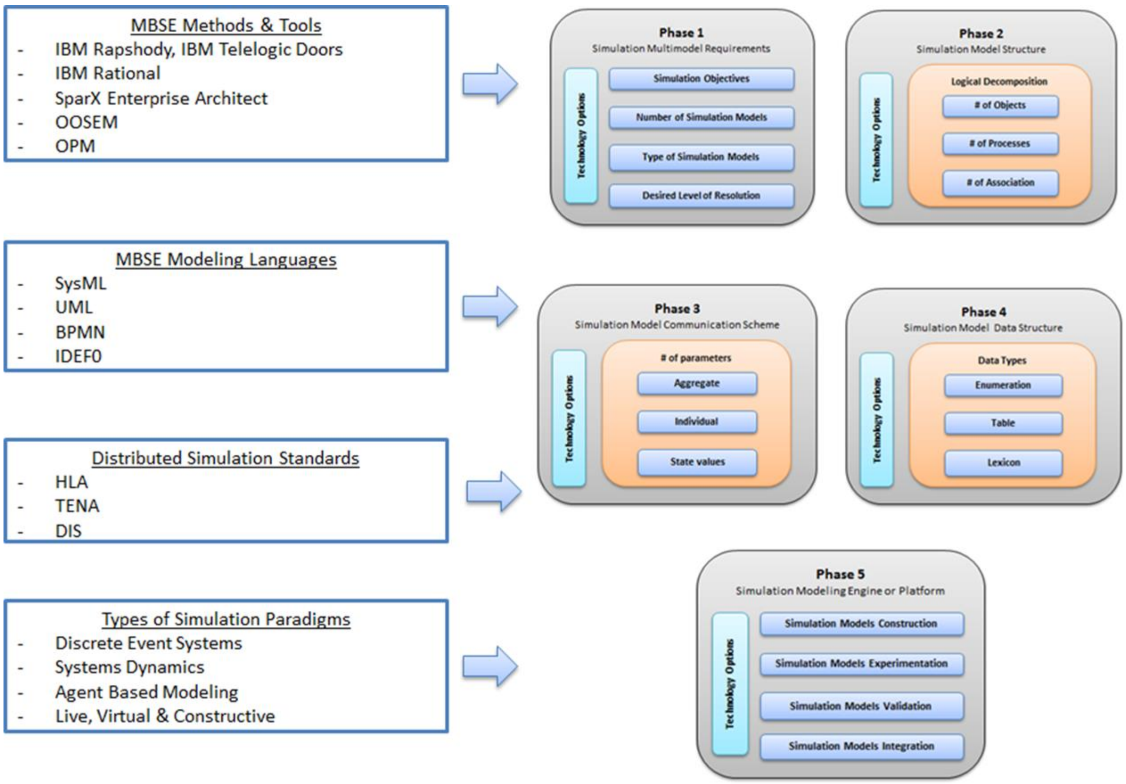


Figure 6-1: Overview of Simulation Development Roadmap

Distributed and hybrid simulation systems are characterized by the need of interoperability standards. The MBSE modeling techniques will enable the definition of interoperable object definitions required for proper intercommunication between acting simulations models in the distributed and hybrid simulation context. Belani et al (2010) discussed the level of conceptual interoperability model (LCIM) in the context of simulation interoperability and composability for the definition of a component-based approach to modeling and simulation. Their research did not include system engineering principles. The adoption of the LCIM concepts can aid in our MBSE based roadmap developmental approach.

In addition, a number of distributed simulation communication protocols can be adopted from industry. Our developmental roadmap approach will refer to the High Level Architecture

(HLA) standard for our experimentation and roadmap definition. Other distributed simulation standards are available in industry. The HLA standard provides a number of simulation object reference models for proper interoperation of hybrid and distributed simulation systems. The standard Federation Object Models (FOM) can be used to define interoperation mechanisms between distributed simulation objects and can be adopted in our methodological guidelines and roadmap.

6.4 Roadmap Description

The first steps in the roadmap are related to understanding the problem and taking into consideration the problem domain to analyze and investigate the alternatives. Interoperability characteristics are discussed in the following steps to ensure proper communication between different simulation environments and simulation models. The benefits of using MBSE methods and tools are discussed and presented.

6.4.1 Simulation Multi-model Requirements

Initially a problem domain is identified with acceptable boundaries corresponding to customer needs. The system to be model must have certain behavioral and functional characteristics that need to be taken into consideration during the requirement discovery process. Simulation objectives will have to be determining that align with the stated problem domain behavioral and functional dimensions. Basically, modeling objectives have to be determined to specify the inputs and output parameters necessary to achieve the intended model behavior and functional characteristics.

MBSE methods and tools can support the development of system requirements definition and functional decomposition of a particular system model. The "Block Definition Diagram" (BDD) in the SysML modeling language allows for system development structures to be defined in a modular "type of tree" arrangement. This modular arrangement allows for the definition of relationships among different BDD diagrams that compose a system structure. Hierarchical composability (sub-models) and model relationships can be established among the BDD diagrams to specify model structure associations, generalizations and dependencies.

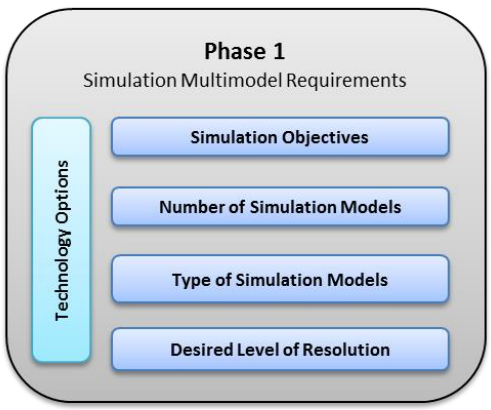


Figure 6-2: Roadmap Phase 1 Diagram

As shown in Figure 6-2, Phase 1 of our distributed and hybrid simulation development roadmap takes into consideration the problem domain to determine the following items:

- Simulation Objectives
- Number of Simulation Models
- Type of Simulation Models
- Desired Level of Resolution

The simulation objectives will be driven by the problem domain behavioral and functional characteristics of the system or process to be simulated. Also, during the requirement discovery process the simulation modeler will determine simulation objectives in accordance with the client system analysis needs. Based on the MBSE survey study modeling and simulation professionals reported that the UML and SysML modeling languages were the most widely used during their simulation system development efforts. Thus, MBSE modeling artifacts that can capture the required system behavioral and functional characteristics from the UML and SysML modeling languages can be utilized to document the simulation objective. In particular, SysML BDD allows for a model decomposition approach that can help determine the definition of the other required items in our Phase 1 development. In addition, SysML has a requirements table modeling artifact that can model system requirement and any required dependencies or derived requirements. A number of MBSE modeling languages (e.g., UML, SysML, BPMN, etc.) and system modeling standards are available in industry to support the development of distributed and hybrid simulation system. MBSE modeling languages, methods and tools to be considered during Phase 1 of development can be associated with the survey data responses to drive client requirement definitions. One important note is that not all MBSE modeling languages provide modeling artifacts to manage requirement modeling. However, a lot of the MBSE methods and tools have requirement management tools that can be managed electronically from the tool and are not necessarily dependent on MBSE modeling artifact capabilities for a diagrammatic representation.

Determining the number of simulation models required to the meet the simulation objectives will be defined in Phase 1 of our developmental roadmap as well. This can help determine the amount of resources to be allocated to the simulation project. Technology options will need to be evaluated to align with our distributed and hybrid simulation roadmap in Phase 1 according to industry standards and the simulation model objectives. Another important Phase 1 item in our roadmap is the different type of simulation paradigms required for the simulation system development. The modeling and simulation professionals will choose what type of simulation or technique to be used for each of the simulation models required based on their experience and in accordance with the problem domain as follow:

- Discrete Event Simulation
- System Dynamic Modeling
- Agent-Based Modeling
- Constructive Simulation
- Virtual Simulation
- Live Simulation

The last step in Phase 1 of our simulation developmental roadmap is to determine the level of resolution required for the simulation models. During the simulation system requirements discovery process different simulation objectives must be determine. The MBSE modeling language artifacts allow for the definition of a hierarchical decomposition (sub-models) and relationship structure among simulation models. BDD diagrams and their relationship with the simulation objective or listed requirements specify simulation model structure associations, generalizations and dependencies possible in different modular arrangements to describe a problem domain. These decomposition arrangements describe the relationships among different BDD diagrams that compose a simulation system structure. Thus, the desired level of resolution can be defined as standard or detailed. Meaning, that as more levels of decomposition are defined for establishing the simulation model objectives or describing the problem domain the higher level of resolution (detailed) would be required. Standard resolution can be consider for simulation models that do not require more than a couple level of structural decomposition to present a particular problem domain.

6.4.2 Simulation Models Structure

Model building is all about providing the right level of abstraction about a particular real life situation and/or problem domain to enable some analysis. Robinson (2008a) defines conceptual modeling as "a non-software specific description of the simulation model that is to be developed, describing the objectives, inputs, outputs, content, assumptions, and simplifications of the model". As discussed throughout this document MBSE can allow simulation engineers to formally model different aspects of a problem ranging from architectures, to corresponding behavioral analysis, to functional decompositions and user requirements (Jobe, 2008). One of the major characteristics of MBSE methodologies is the use of modeling languages (i.e., UML, SysML, BPMN, EFFBD and OPDs/OPL) and tools with data and model management applications that support interdisciplinary system development and collaboration efforts. Phase 2 development efforts in our roadmap definition can use MBSE method and tools to define the simulation models structures that will satisfy the simulation system objectives described during Phase 1 of the developmental roadmap.

Conceptual modeling principles can support Phase 2 developments with adequate simulation model structures and decompositions about a problem domain to enable the understanding of processes and objects that can describe a specific domain. A particular problem domain is not necessarily simple in structure. Meaning, a simulation model might need to be defined in a modular and hierarchical fashion to enable proper representation of a system or process. Simulation models can have different levels of complexity and conceptual modeling approaches can simplify the model building process. In general, conceptual modeling promotes and supports the reusability, interoperability and composability of simulation models.

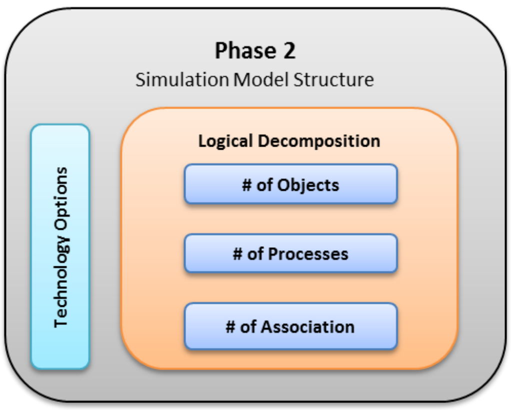


Figure 6-3: Roadmap Phase 2 Diagram

As shown in Figure 6-3, Phase 2 of our distributed and hybrid simulation developmental roadmap takes into consideration the type of simulation models and their respective level of resolution required to determine the simulation model structure items as listed here:

- Number of Simulation Objects
- Number of Simulation Processes
- Number of Associations

MBSE modeling languages can enable simulation models structure definitions and logical decompositions in our Phase 2 developmental efforts to meet the simulation objectives. Phase 2 simulation objects and processes are the main modeling items to consider for describing a particular problem domain in our simulation system development efforts. Tolk and Turnista (2012) in the context of conceptual modeling express that simulation object and process definitions and their particular attribute and parameter relations enable knowledge representations about a particular problem domain. Our particular Phase 2 development efforts refer to object and process relationships as "associations" to take advantage of the MBSE SysML association diagram modeling artifact.

Turnista (2012) presents the object-process-relationship (OPR) modeling technique developed through his dissertation work. His work discusses the application of the OPR method in the conceptual modeling domain and its applicability with MBSE methods and modeling languages. Initially, he discusses the applications of the UML modeling language artifacts in relation to his OPR method. Further, his efforts describe the implementation of the OPR conceptual modeling technique with the MBSE "Object Process Methodology" (OPM) as this method defines modeling techniques to describe process to process relationships. The OPM technique is a system modeling approach that uses the "Object Process Language" (OPL) and the "Object Process Diagrams" as their integrated modeling language and modeling artifacts to describe a system. Using the survey response data to guide our developmental roadmap description we found that less than 5% of distributed and hybrid simulation practitioners had used the OPM method and its associated OPL/OPD modeling language and artifacts.

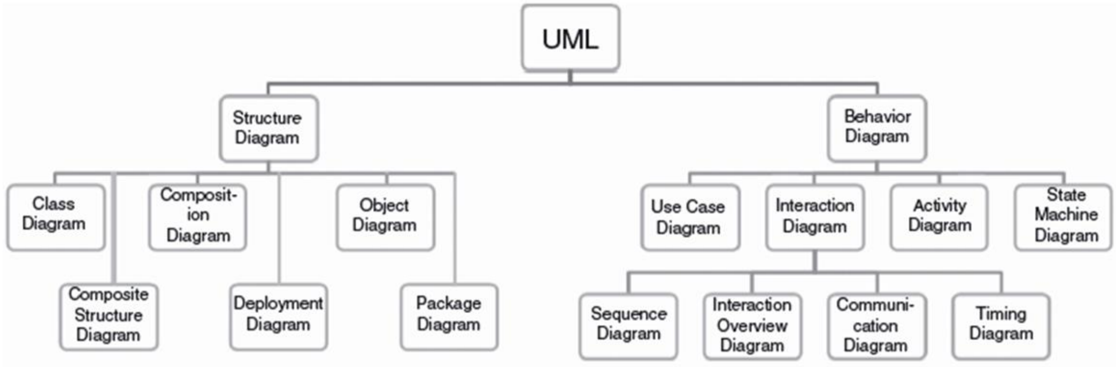


Figure 6-4: UML Diagram Hierarchy (Tolk, 2012)

In addition, our survey response data indicated that UML and SysML were used the most in recent simulation system developments among the distributed and hybrid simulation practitioners with 81% and 52% respectively. Tolk and Turnista (2012) discuss that UML and SysML have more than fourteen diagrammatic techniques that can be used to represent simulation models structures and their object and process associations or relationships. Tolk (2012) notes that the UML modeling language is particularly defined to support modeling efforts in the software engineering domain even though the industry reports many application to business modeling as well. Figure 6-4 illustrates the UML diagrams and modeling artifacts hierarchy. In addition, Tolk (2012) expresses that UML diagrams are good for describing either structure or behavior that are usually related to "classes that represent type information (properties shared by all things of this type) and objects that represent instance information (properties exposed by the individual instantiations of a thing of a given type)" (p. 218).

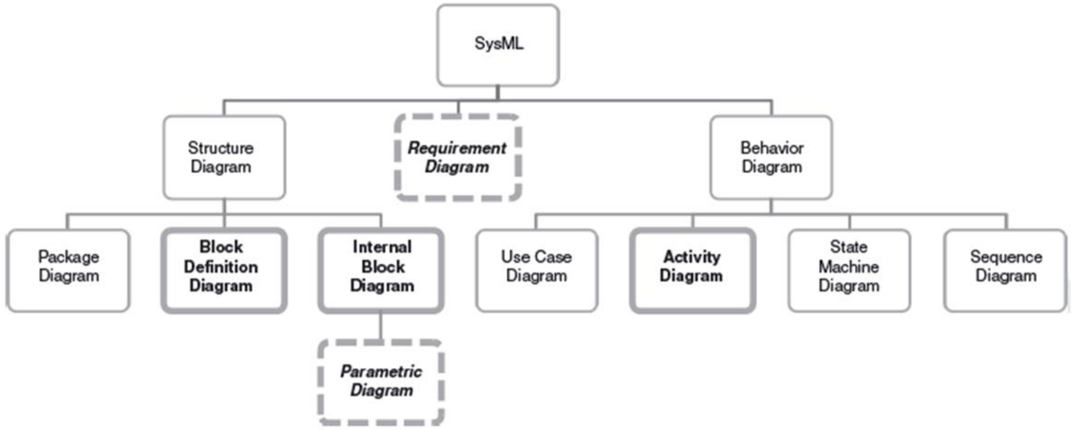


Figure 6-5: SysML Diagram Hierarchy (Tolk, 2012)

Further, Tolk (2012) explains that UML is finds its roots in the object oriented methods that govern software engineering practitioners. But he further states that SysML is founded in systems engineering principcles. Thus, to establish process to process, object to object and object to process associations we recommend the use of SysML “Ports and Flows” and “Constraint Blocks” modeling artifacts among other modeling artifacts. Figure 6-5 shows the SysML diagram hierarchy.

6.4.3 Simulation Models Communication Scheme

Distributed and hybrid simulation systems need to exchange data during interaction between different simulation models. Semantic interoperability is related to the grammatical consistency that represents the data being interchange between the models. The data can be represented by a single set of values or an aggregate representation of a particular simulation object attributes or interaction parameters.

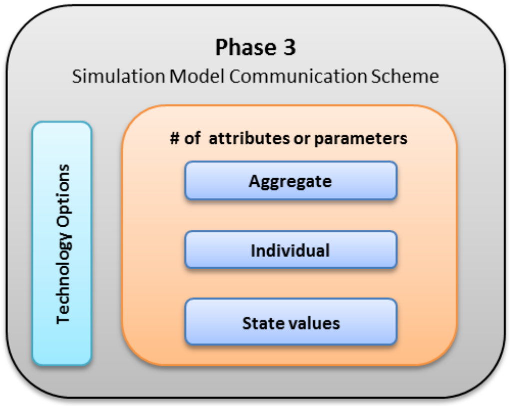


Figure 6-6: Roadmap Phase 3 Diagram

As shown in Figure 6.6, Phase 3 of our distributed and hybrid simulation developmental roadmap takes into consideration the number of attributes and parameter require for simulation models interoperation and their respective communication scheme item type as listed here:

- Aggregate
- Individual
- State Value

Phase 3 development efforts should adopt a distributed systems communication standard in industry that enable the semantic type of communication scheme between the different simulation models. Technology options for distributed systems communication standards include HLA, TENA and DIS among others that not only support interoperability between simulation models but also assists with semantics issues. Our simulation development roadmap experimentation adopts the HLA standards for interoperation of simulation models. In this standard a Federation Object Model (FOM) semantic structure can be defined to dictate what type of data is being exchanged between simulation objects in the distributed simulation environment. Thus, in an HLA based distributed simulation environment the FOM describes the data translations in terms of classes, attributes and parameters.

The industry has defined a number data translation schemes based on the HLA standard. These translation schemes are called "Real-time Platform-Level Reference FOM" (RPR – FOM). A number of RPR-FOM data translation schemes have been developed in industry for the different HLA standards (HLA 1.3, HLA 1516 and HLA 1516 evolved). The RPR-FOM in the distributed and hybrid simulation community can be seen as the common starting point for "data content exchange" between distributed simulation models. This industry agreed "data content exchange" standard can be implemented for aggregate or individual levels of data. The RPR-FOM is rooted in the ability of HLA distributed simulation systems to interpret DIS "protocol data units" (PDU) which governed legacy standalone military simulation systems. In those efforts, as described by Tolk (2012) the RPR-FOM main idea was to map PDU into HLA object and interaction classes. The structure of the object and interaction classes can be seen in Figure 6.7 which describes the RPR-FOM classes.

The RPR-FOM promotes a common communication scheme among HLA based distributed simulation systems in which federates (simulation models) have an agreed object and interaction "data content exchange" scheme between distributed simulation models. Phase 3 development can leverage from this data communication scheme effectively implement HLA based distributed simulation systems that can exchange the right amount of data, at the right time and that enables adequate interoperability and reuse capabilities among distributed simulation models in the system.

Class 1	Class 2	Class 3	Class 4
BaseEntity	PhysicalEntity	Platform	Aircraft
			AmphibiousVehicle
			GroundVehicle
			Spacecraft
			SurfaceVessel
			SubmersibleVessel
			MultiDomainPlatform
		Lifeform	Human
			NonHuman
		Sensor	
		Radio	
		Munition	
		CulturalFeature	
		Expendables	
		Supplies	
	EnvironmentalEntity		
EmbeddedSystem	Designator		
	EmitterSystem		
	RadioReceiver		
	RadioTransmitter		
EmitterBeam	RadarBeam		
	JammerBeam		

Figure 6-7: RPR-FOM classes (Tolk, 2012)

6.4.4 Simulation Models Data Structure

The development of distributed and hybrid simulation systems is a top-down level approach. In order to achieve the desirable level of interoperability the conceptual modeling should enable the description of processes, states and operation between the simulation models. A shared understanding is only possible if a specified information structure is achieved from top to bottom. Interoperability integration leverages from distributed simulation standards as HLA that enable the right simulation models data structure among acting distributed simulation models. This integration is at the syntactic level. In the HLA domain different simulation models (federates) can communicate through structure content interactions described by the FOM

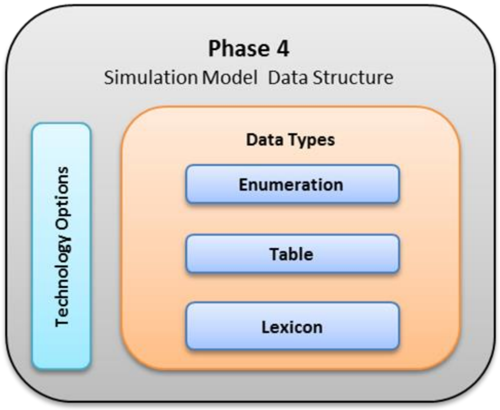


Figure 6-8: Roadmap Phase 4 Diagram

As shown in Figure 6.8, Phase 4 of our distributed and hybrid simulation developmental roadmap takes into consideration simulation models data structures. Object and process HLA based interactions among distributed simulation models exchange structured data in an agreed FOM. This structure data exchange can be identified by different data types. The HLA distributed simulation standard allows for the configuration of different data type that can be considered in our Phase 3 development efforts and some of this data types are listed here:

- Enumeration
- Table
- Lexicon

The Federation Object Model (FOM) can describe the structure content that will be translated between interoperating simulations due to an agreed syntactic protocol that commercial software solutions support. In the case of the HLA standard this is the Object Model Template (OMT). Basically, the OMT is a common content structure for describing HLA simulation objects models (SOM) and FOM which enable data consistency during simulation interactions. The types of objects and interactions that a simulation model can produce and consume are defined through standard HLA SOM and FOM. The object, its attributes, the interactions and the interaction parameters that enable proper implementation of processes, states and operation between the simulation models are possible by the OMT standard. Depending on the simulation engine capabilities and simulation paradigm OMT modification or syntactic modeling (or configuration) is required to enable the proper simulation interoperability between different simulation engines or platforms.

6.4.5 Simulation Modeling Engine or Platform

Once all the preceding steps or phases in our defined simulation developmental roadmap are conducted meaningful model construction and experimentation can be achieved. Proper interoperability of distributed and hybrid simulation systems is not a matter of hardware or software implementation. It is a process that is attained by an adequate conceptual modeling practice. Wang (2009) expressed that proper interoperability is achieved when technical structures are closely aligned with the conceptual ideas. Thus, a top-down approach is necessary during development of distributed and hybrid simulation systems starting with conceptual modeling. MBSE methods and tools have the necessary means to establish that interoperability requirement at the conceptual modeling level. Starting from the definition of simulation requirements MBSE enables the proper behavioral and functional characteristics of simulation models. Based on the modeling objectives input and output parameters will allow for adequate experimentation and analysis of a simulation problem domain.

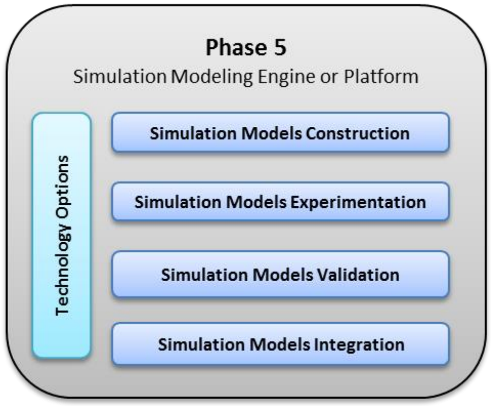


Figure 6-9: Roadmap Phase 5 Diagram

As shown in Figure 6.9, Phase 5 of our distributed and hybrid simulation developmental roadmap takes into consideration the simulation modeling engine or platform to enable the proper construction of simulation models that are representative of the problem domain and can satisfy the simulation objectives defined in Phase 1 of our roadmap. In this final developmental phase in our roadmap the integration of the different simulation models is done in accordance with all the conceptual modeling descriptions established during the earlier phases of development. Items in Phase 5 development efforts are listed here:

- Simulation Models Construction
- Simulation Models Experimentation
- Simulation Models Validation
- Simulation Models Integration

During simulation models construction interoperability concerns for each particular simulation model types (DES, Constructive, Virtual, etc.) must implement all necessary behavioral and functional characteristics to ensure proper interaction between distributed simulation models. Van der Aalst, (2004) explained that the used of system engineering modeling languages can support a well-structured process or modeling techniques to provide the right level of expressiveness, simplicity and formal semantics required for the implementation of hybrid simulation systems. MBSE modeling techniques and tools are considered during our simulation developmental roadmap and SysML/UML modeling artifacts integrate the HLA distributed simulation standards in the definition of architectural designs and distributed system structures throughout previous phases in the roadmap. The survey response data indicated that UML and SysML were used the most in recent simulation system developments among the distributed and hybrid simulation practitioners with 81% and 52% respectively. Thus, simulation model construction can be guided by the previously defined model structures and communication schemes documented by the MBSE to facilitate proper interoperation between the different simulation model types.

Simulation models experimentation and validation are other developmental items in Phase 5 of our roadmap. Models will need to be verified through experimental methods to ensure proper interoperability. Distributed simulation standard compatibility is to be expected of the simulation modeling engines or platforms. In the case of our developmental roadmap we considered the HLA standard for distributed simulation systems. The HLA standard allows for the definition of a federation that allows different simulation models (federates) to interact with each other through the use of a “Runtime Interface” (RTI) middleware that allows the information exchange between the simulation systems (Tolk, 2012). Phase 5 in our roadmap is where the simulation models integration is executed. As discussed in the previous phases in our roadmap communication schemes and data structure characteristics are technology items during integration that are implemented by the distributed simulation system standards. In the case of HLA, the “Object Model Template” (OMT) and the “Federate Object Model” (FOM) are technology items that enable the proper configuration of the distributed simulation system. The FOM dictates what type of information is being exchanged between simulation objects and their interactions in the distributed simulation environment. The OMT provides a formal “content structure” for the data exchange (data types) between the simulation objects, process and their particular associations. The HLA distributed simulation standard allows for proper configuration of different data types between the different simulation engines through an RTI middleware. VT MAK Technologies (www.mak.com) and Pitch Technologies (www.pitch.se) are some of the leading providers of RTI middleware for distributed simulation systems implementations.

The simulation modeling engines or platforms allow for proper configuration of RTI middleware for implementing distributed simulation systems. Depending on the simulation engine capabilities and simulation paradigm OMT modification or syntactic modeling (or configuration) is required to enable the proper simulation interoperability between different simulation engines or platforms.

CHAPTER 7. CASE STUDY #1 – PORT MARITIME OPERATIONS

The previous chapter discussed the definition of a distributed and hybrid simulation development roadmap that combines the available MBSE methodologies and tools in a structured and ordered process to support the definition, analysis and development of distributed and hybrid simulation systems. This chapter presents a case study to exercise our developmental roadmap and show its application capabilities for the proper architecting and implementation of distributed and hybrid simulation systems. Throughout this case study our distributed and hybrid simulation developmental roadmap guidelines and recommendations will be presented.

7.1 Case Study Introduction

This case study presents the development of a hybrid simulation modeling environment for the carbon footprint of a port system in Panama using the High-Level Architecture (HLA). The Balboa Port in Panama is the largest port in Latin America with a growth rate of 14% in the last three years. A calibrated discrete model of the port was developed to represent the security gate operations and heavy duty diesel vehicle (HDDV) truck deliveries. Another discrete-event federate represents the vessels arriving at the different terminals. Finally, a simple continuous simulation model is a federate that contributes to measure the carbon footprint due to the operations in the port. The carbon footprint continuous simulation model federate is a systems dynamic model that can specify an estimate of the greenhouse gas (GHG) emissions that originate from the delivery of cargo load containers. In addition, estimation of the GHG emissions are also performed for the HDDV truck deliveries using a discrete-event federate as the source of the required events. This case study discusses the hierarchical distributed and hybrid simulation approach to the Port Maritime Operations at the Port of Balboa (Panama) show in Figure 7-1. Ultimately, this case study will be used for the testing our simulation development roadmap based on an MBSE methodology approach to lifecycle modeling of distributed and hybrid simulation systems.

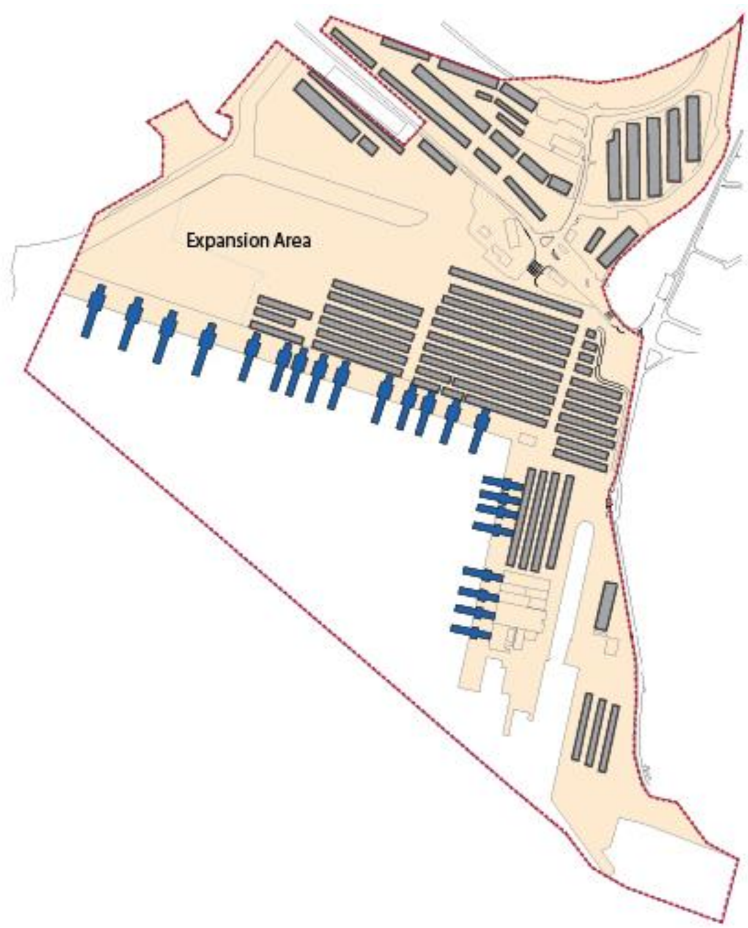


Figure 7-1: Port of Balboa – Republic of Panama

7.2 Port of Balboa Maritime Operations

With the privatization of public ports in Panama since 1995, significant increase in the container activity has been observed at the Panamanian ports. By 2011, these ports have become one of the busiest container terminals in the Latin America, with a growth rate of 20% for the Atlantic terminals and 17.2% for Port of Balboa in the Pacific. The mean growth rate for the rest of the main container terminals in Latin America was 12.3% (Perez, 2012). Port of Balboa is located at the Pacific entrance of the Panama Canal. It shares seaside operations with the Panama Canal due the fact that it is located alongside the inner access channel of the Panama Canal.

Handling an estimate of 3.2 million Twenty Foot Equivalent Units (TEUs) annually implies more than 1,300 containership arrivals, spread within a weekly average of 25 calls. Port of Balboa is a 90% transshipment hub terminal and uses Rubber Tire Gantry Cranes (RTGs) - Tractor Trailer Units (TTU) system as horizontal means of transport between the Gate – Storage – Berth subsystems and traditional quay cranes to serve the ships. While latest arrived RGTs at the port use hybrid energy systems (electric and fuel), TTUs are heavy duty diesel vehicles (HDDV).

However, with the growth of the ports, the human activity and greenhouse gas emissions increase. It is estimated that 5.5% of the total human activity generated annual greenhouse gas emission are contributed by the logistics and transport sector (Doherty, 2009). Moreover, 75% of this previous estimate is contributed from the transport activities in the logistics chain. Based on this, logistics companies like DHL, DBahn and Tesco, have established goals to reduce their emissions from 20% to 30 % by 2020 (Piecyk, 2013).

Considering this growth in activities at the Balboa port, a modeling environment for estimating carbon footprint of a port system in Panama Canal is to be implemented using HLA

(High Level Architecture) and RTI (Run Time Infrastructure). The basic federates in the configuration are explained as below:

- A discrete event model of gate operations at the port of Balboa was developed in AnyLogic representing security gate and heavy duty diesel vehicle (HDDV) truck deliveries.
- The port berthing process at port of Balboa was developed to be implemented as a federate using a discrete event model implemented in Anylogic. Real time data related with ships such as number of resources, interarrival times and service times were used in implementation of this model.
- A carbon footprint federate is defined as a continuous simulation model developed using system dynamics modeling techniques in AnyLogic. This model measures Greenhouse gas (GHG) emissions which originate from the delivery of cargo load containers and various activities in the port.
- A final visualization federate is defined as a virtual simulation platform using the Simbox engine developed by SimiGon. The virtual platform allows for terminal operation center personnel performed visual inspection of the berth and gate operation at the port.

The distributed and hybrid simulation environment is being developed using HLA/RTI and will allow for the execution of the Port, Gate and carbon footprint simulation models in order to visualize the overall port operations and the carbon footprint measurements. Phase 1 guidelines in our roadmap were applied to the Port of Balboa Maritime Operations and details are included in Table 7-1.

Table 7-1: Case Study #1 – Phase 1 Roadmap Simulation Requirement Details

Items	**Description**
Objectives	Replicate and study port container handling operations Model the berthing and gate operations Study ecological footprint due to increase forecast of container handlings per year
Number of Models	Berthing/Discrete-Event/Detail Gate Operations/Discrete-Event/Detail Ecological Footprint/System Dynamics/Standard Visualization/Virtual/Standard
Type Models	Discrete-Event/AnyLogic Systems Dynamics/AnyLogic Virtual Simulator/Simigon
Level of Resolution	Standard Detail

In the proposed distributed and hybrid simulation approach a number of simulation models have been defined to participate as acting federate simulation systems. The most appropriate type of simulation is determined by the simulation modeler. In addition, the level of resolution is selected according to the level of decomposition required to achieve the right level of abstraction about the problem domain and system. The simulation engines proposed for the simulation systems as detailed in Table 7-1 are AnyLogic (www.anylogic.com) for the Discrete-Event and System Dynamics models and Simigon (www.simigion.com) for the Virtual simulation application. The next subsections describe the simulation models and associated guidelines in our developmental roadmap.

7.2.1 Port Model – Berthing Process

The port model for the berth subsystem was analyzed from a technical and operative perspective. Technical aspects taken into consideration were infrastructure and superstructure available (quays and quay cranes at berths) as well as characterization of customers (containership structural size and workload). On the other hand, operative aspects are service strategies implemented by the terminal that have an impact, together with the technical considerations, on key performance and environmental indicators measured in this subsystem. Some of these measurements in the process are the frequency of calls and time the ship or "entity" spends in each part of this terminal subsystem. Phase 2 guidelines in our roadmap were applied to the berthing model and details are included in Table 7-2.

Table 7-2: Case Study #1 – Phase 2 Roadmap Berth Model Details

Component	Details	Items	MBSE Language/Diagrams
Entities	Container Ship	Objects	SysML/BDD & Class
	Containers	Objects	SysML/BDD & Class
	Tug Boats	Objects	SysML/BDD & Class
Activities	Loading	Process	BPMN/Workflow
	Offloading	Process	BPMN/Workflow
	Customs	Process	BPMN/Workflow
	Berth Assignment	Process	BPMN/Workflow
Queues	Wait for Inspection	Associations	SysML/Sequence & State
	Wait for Berth Assignments	Associations	SysML/Sequence & State
Resources	Quays	Associations	SysML/Sequence & State
	Quay Cranes	Associations	SysML/Sequence & State

This case study work was done in collaboration with the International Maritime University of Panama (UMIP). As noted in the survey response data UML and SysML were used the most in recent simulation system developments among the distributed and hybrid simulation practitioners. However, as we gathered data for the port operations the modeling team decided to document the simulation model structure using the Business Process Modeling Notation (BPMN) in this developmental phase as personnel at the Port of Balboa in Panama could have difficulties with the software engineering and system oriented nature of the UML and SysML modeling language approach. For this reason, the berthing process at port of Balboa shown in Figure 7-2 was described BPMN.

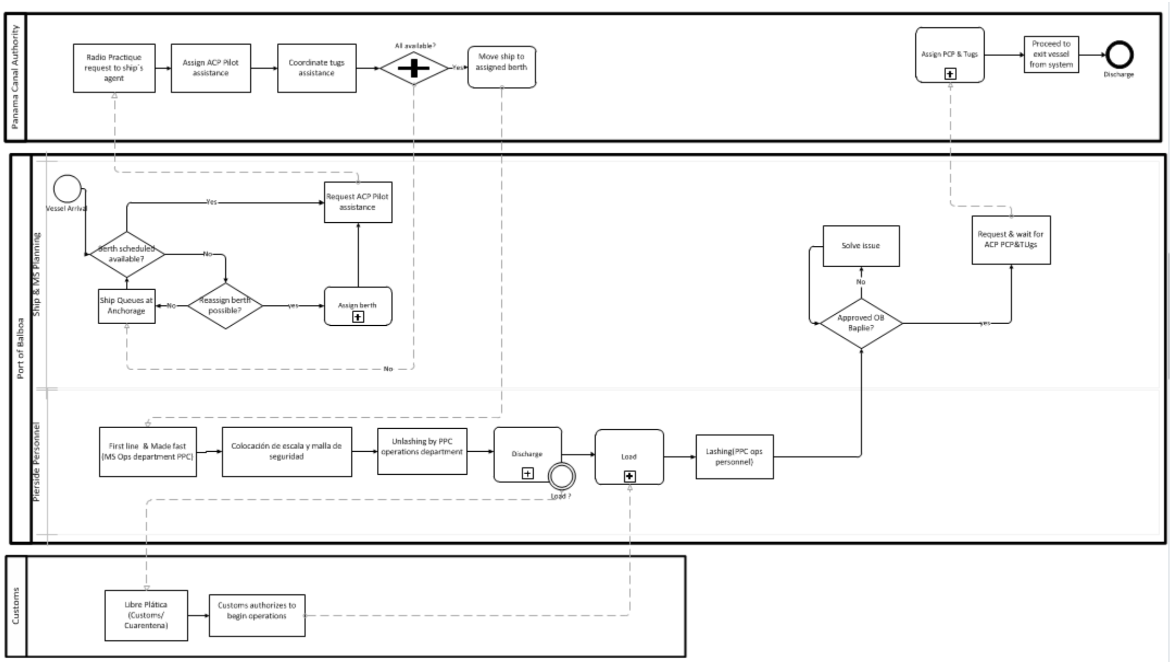


Figure 7-2: Port at Balboa Berthing Process

The following lists provides a procedural description of the berthing process that was captured in Figure 7-2 and supports the simulation model structure details captured in Table 7-1:

- The containership arrives at anchorage based on berthing windows.
- In the model arrivals are model in a mixed composition of probability distributions and Schedules. If the vessel arrives in its expected berth window or exists the possibility to begin the berthing process, Port of Balboa Ship Planners and Marine Service

Departments request Panama Canal Pilots (PCP) and Tugs assistance for moving the vessel from anchorage to its corresponding berth.

- In case PCP - and Tugs are available for placing vessel at berth, these resources move the vessel to the assigned berth, otherwise, go to next step. Ship queues at anchorage until all resources in step 2 are available.
- The queue presents a mixed behavior of First in First Out sequence plus the assigned priority logic.
- Marine Service Department from Port of Balboa proceeds to moor vessel in berth.
- Customs inspects load documentation while discharge is being processed by the container terminal.
- Yard and Ship Departments coordinate and monitor load and discharge processes.
- When load sub process is done, the ship planner asks for the Chief Officer´s Outbound Baplie approval which is an electronic data file given from the Port Terminal to the carrier that contains the load planning bays of vessels carrying containers.
- Once approved the Outbound Baplie the vessel has to be removed from the system by the PCP and Tug Company.

7.2.2 Port Gate Operations

The gate and landside access is another subsystem of the terminal. The Gate in turn is made of the following components: Entry/Exit gates, "Precheck" Area, Gatehouse and Lane. Each of these components has its own set of processes. Phase 2 guidelines in our roadmap were applied to the gate operations model and details are included in Table 7-3.

Table 7-3: Case Study #1 – Phase 2 Roadmap Gate Operations Model Details

Component	Details	Items	MBSE Language/Diagrams
Entities	Trucks	Objects	SysML/BDD & Class
	Containers	Objects	SysML/BDD & Class
	Gate Operators	Objects	SysML/BDD & Class
	Yard Cranes	Objects	SysML/BDD & Class
Activities	Container Weighing	Process	BPMN/Workflow
	Pre-check	Process	BPMN/Workflow
	Gate	Process	BPMN/Workflow
	Customs	Process	BPMN/Workflow
	Yard Assignment	Process	BPMN/Workflow
	Exit	Process	BPMN/Workflow
Queues	Wait for Inspection	Associations	SysML/Sequence & State
	Wait for Yard Assigment	Associations	SysML/Sequence & State
Resources	Weighing Bridge	Associations	SysML/Sequence & State
	Precheck Worker	Associations	SysML/Sequence & State
	Gate Worker	Associations	SysML/Sequence & State

Further, the gate operations process main processes are handling the import and export of containers. One important fact in this process it that full containers and empty containers do not have the same services times. In fact, what is considered a “full” container movement is priced higher than an empty container. In addition, a full container movement takes 35% more time to process than movement of empty containers. The import and export gate operation processes were modeled using BPMN. Figure 7-3 illustrates the export process that containers undergo at the port gate and landside of the maritime operations at Port Balboa and Figure 7-4 illustrates the import process of the containers.

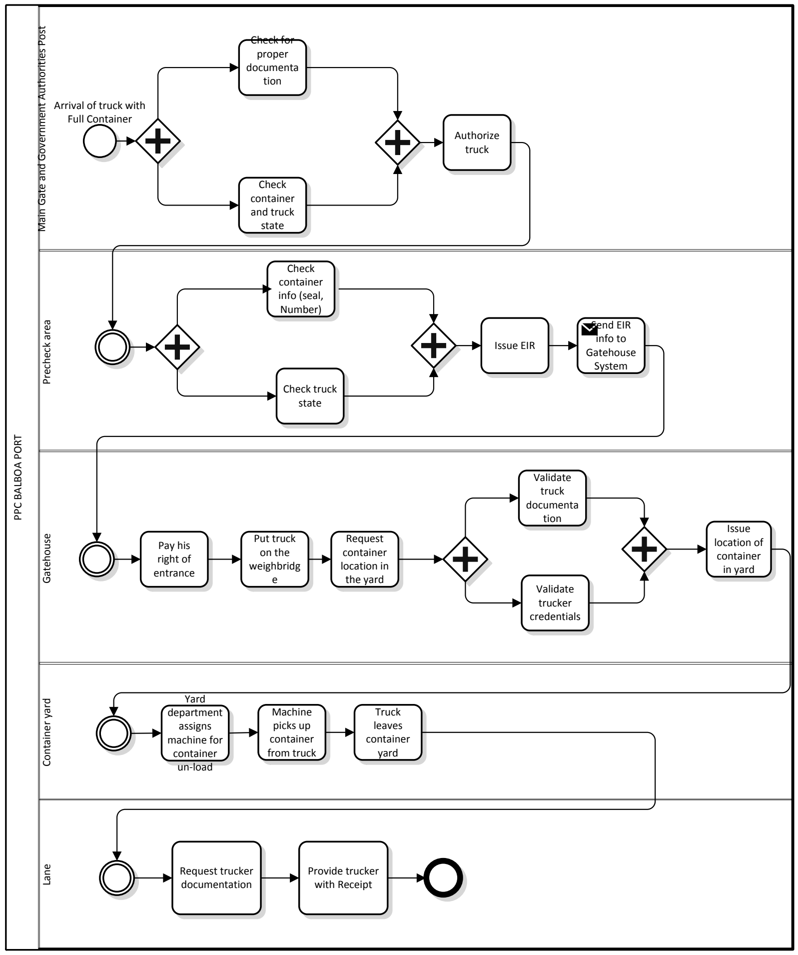


Figure 7-3: Gate Operations Export Process

The BPMN models supported the Phase 2 development of the gate operations discrete event simulation model. The gate and landside subsystem are grouped in two main process flows which are identified as the outbound flows (import of full containers, pick up of empty containers) and inbound flows (export of full containers, delivery of empty containers). Phase 2 guidelines described in Table 7-3 provides the simulation model structure details identified by the simulation modeling team to provide the right level of abstraction during simulation model construction.

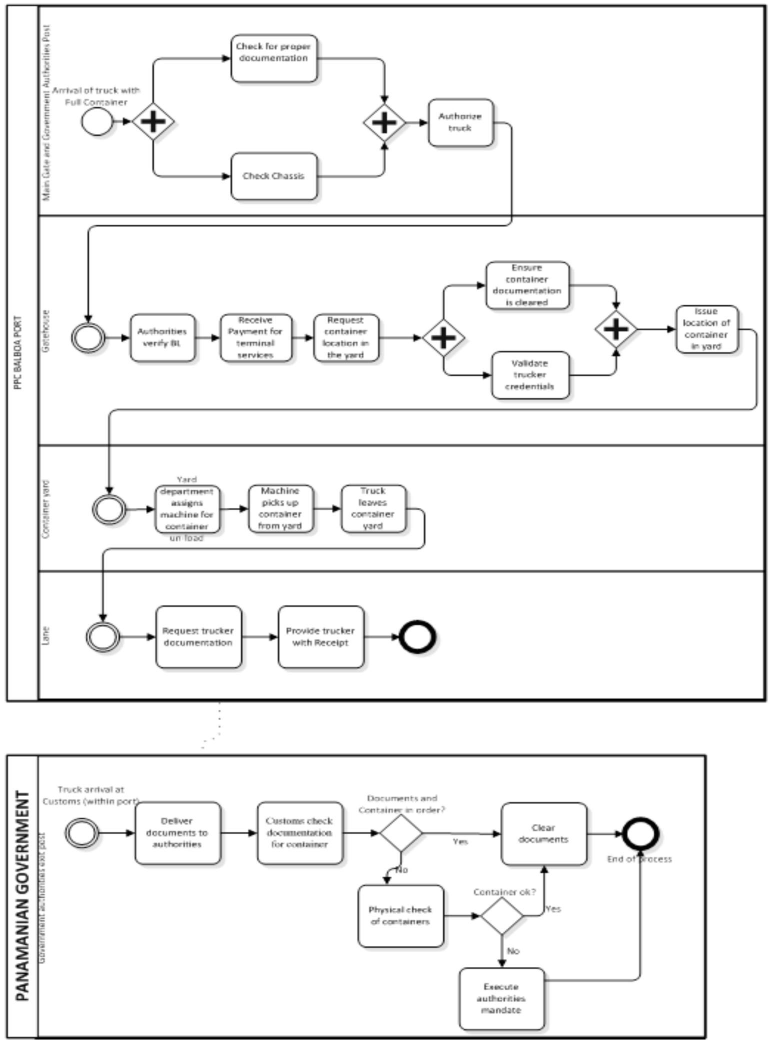


Figure 7-4: Gate Operations Import Process

7.2.3 Port Carbon Footprint Model

A Carbon Footprint model was needed to study the ecological impact of the growth in container handling at the Port of Balboa. Phase 2 of the developmental roadmap details the carbon footprint model structure details and is shown in Table 7-4.

Table 7-4: Case Study #1 – Phase 2 Roadmap Simulation Model Details

Component	Details	Items	MBSE Language/Diagrams
Entities	Trucks	Objects	SysML/BDD & Class
	Container Ship	Objects	SysML/BDD & Class
	Tug Boats	Objects	SysML/BDD & Class
	Yard Cranes	Objects	SysML/BDD & Class
Activities	Gate Operations	Process	BPMN/Workflow
	Berth Assignment	Process	BPMN/Workflow
	Yard Assignment	Process	BPMN/Workflow
Queues	Wait for Inspection	Associations	SysML/Sequence & State
	Wait for Berth Assignments	Associations	SysML/Sequence & State
	Wait for Yard Assigment	Associations	SysML/Sequence & State

The emission model was developed using an equation that calculates emission (in kg) of greenhouse gases and it is described as follows (Herbert Engineering Corp., 2011):

$$Emissions = engine\ power \times load\ \ factor \times emission\ factor \times aux.fuel\ consumption \quad (1)$$

Where, engine power is maximum continuous rating of vessel engine in use. Load factor represents percentage of maximum power used by the vessel for in-port operations mode. Emission factor value is expressed as quantity of a pollutant released in the atmosphere with respect to activity responsible for release of pollutant. By multiplying the appropriate fuel based emission factor by the specific fuel consumption in auxiliary mode, emission factors for CO2 and N2O (kg / tone fuel) were converted to power based emission factors (kg/ kW-hr). Emissions of nitrous oxide can then be converted to Carbon Dioxide Equivalents by multiplying the emissions of nitrous oxide by the Global Warming Potential values.

7.3 Hybrid Distributed Simulation of Port Maritime Operations

Our simulation development roadmap presented in Chapter 6 can support the analysis and development of a distributed and hybrid simulation system of the Port Maritime Operations at the Port of Balboa (Panama). The distributed and hybrid simulation system can be developed using the HLA distributed simulation systems standard.

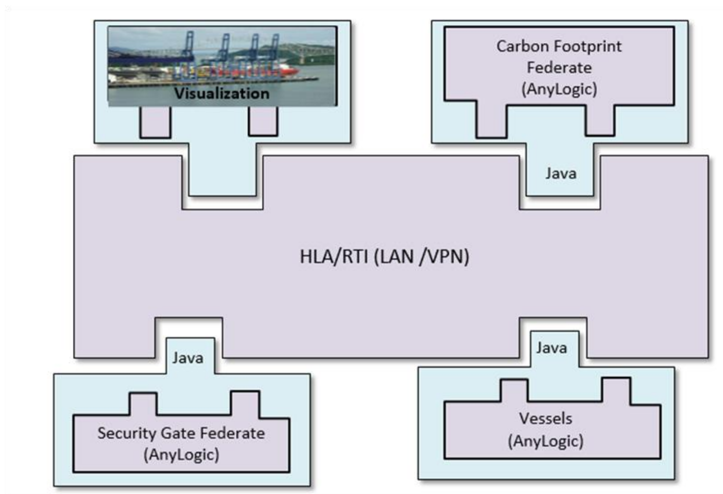


Figure 7-5: Distributed and Hybrid Simulation System for Port Maritime Operations

The simulation developmental roadmap enables the proper conceptual modeling approach to define the required number of attribute and parameters that will provide the means for an adequate interoperation between the different simulation models. The HLA standard provides all the necessary mechanism to define the appropriate type of information exchange between the models and also the right data exchanges structure to safeguard proper interoperability in the simulation system. Proper semantic and integration analysis is done thru Phase 3 and Phase 4 of our developmental roadmap.

Table 7-5 illustrates Phase 3 details for the port maritime operations in terms of attributes and parameters necessary for interoperation between simulation models. The semantic structure can be defined to dictate what type of data is being exchanged between simulation objects in the distributed simulation environment.

Table 7-5: Case Study #1 – Phase 3 Roadmap Simulation Models Communication Details

Component	Details	Items	Standard	MBSE Language/Diagrams
Attributes	Engine type	individual	HLA/SOM	SysML/IBD, Parameter & Class
	Speed	individual	HLA/SOM	SysML/IBD, Parameter & Class
	Location	individual	HLA/SOM	SysML/IBD, Parameter & Class
	Truck type	individual	HLA/SOM	SysML/IBD, Parameter & Class
	Container type	individual	HLA/SOM	SysML/IBD, Parameter & Class
Parameters	Time in the system	aggregate	HLA/FOM	SysML/IBD, Parameter & Class
	Interarrival rates	aggregate	HLA/FOM	SysML/IBD, Parameter & Class
	Rate of fuel consumption	aggregate	HLA/FOM	SysML/IBD, Parameter & Class
	Service times	aggregate	HLA/FOM	SysML/IBD, Parameter & Class
Queues	Wait for Inspection	state	HLA/FOM	SysML/IBD, Parameter & State
	Wait for Yard Assignments	state	HLA/FOM	SysML/IBD, Parameter & State
Resources	Weighing Bridge	state	HLA/FOM	SysML/IBD, Parameter & State
	Precheck Worker	state	HLA/SOM	SysML/IBD, Parameter & State
	Gate Worker	state	HLA/SOM	SysML/IBD, Parameter & State

The types of objects and interactions that a simulation model can produce and consume are defined through standard HLA SOM and FOM. The object, its attributes, the interactions and the interaction parameters that enable proper implementation of processes, states and operation between the simulation models are possible by the OMT standard. Depending on the simulation engine capabilities and simulation paradigm OMT modification or syntactic modeling (or configuration) is required to enable the proper simulation interoperability between different simulation engines or platforms.

Table 7-6: Case Study #1 – Phase 4 Roadmap Simulation Models Data Structure Details

Component	Details	Data Type	Standard	MBSE Language/Diagrams
Attributes	Engine type	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Speed	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Location	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Truck type	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Container type	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
Parameters	Time in the system	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Interarrival rates	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Rate of fuel consumption	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Service times	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Yard Assignment	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
Queues	Wait for Inspection	enumerated	HLA/OMT	SysML/IBD, Parameter & State
	Wait for Yard Assignments	enumerated	HLA/OMT	SysML/IBD, Parameter & State
Resources	Weighing Bridge	enumerated	HLA/OMT	SysML/IBD, Parameter & State
	Pre-check Worker	enumerated	HLA/OMT	SysML/IBD, Parameter & State
	Gate Worker	enumerated	HLA/OMT	SysML/IBD, Parameter & State

In summary, the implementation of the developmental roadmap will ensure proper architecting and implementation of distributed and hybrid simulation systems. The HLA distributed simulation standard allows for proper configuration of different data types between the different simulation engines through an RTI middleware. VT MAK Technologies (www.mak.com) and Pitch Technologies (www.pitch.se) are some of the leading providers of RTI middleware for distributed simulation systems implementations.

The simulation modeling engines or platforms allow for proper configuration of RTI middleware for implementing distributed simulation systems. Depending on the simulation engine capabilities and simulation paradigm OMT modification or syntactic modeling (or configuration) is required to enable the proper simulation interoperability between different simulation engines or platforms.

The simulation construction Phase 5 of the developmental roadmap considered all the simulation model definitions done in the previous steps. Figure 7-6 illustrates the berthing process discrete-event simulation in accordance with the Table 7-2.

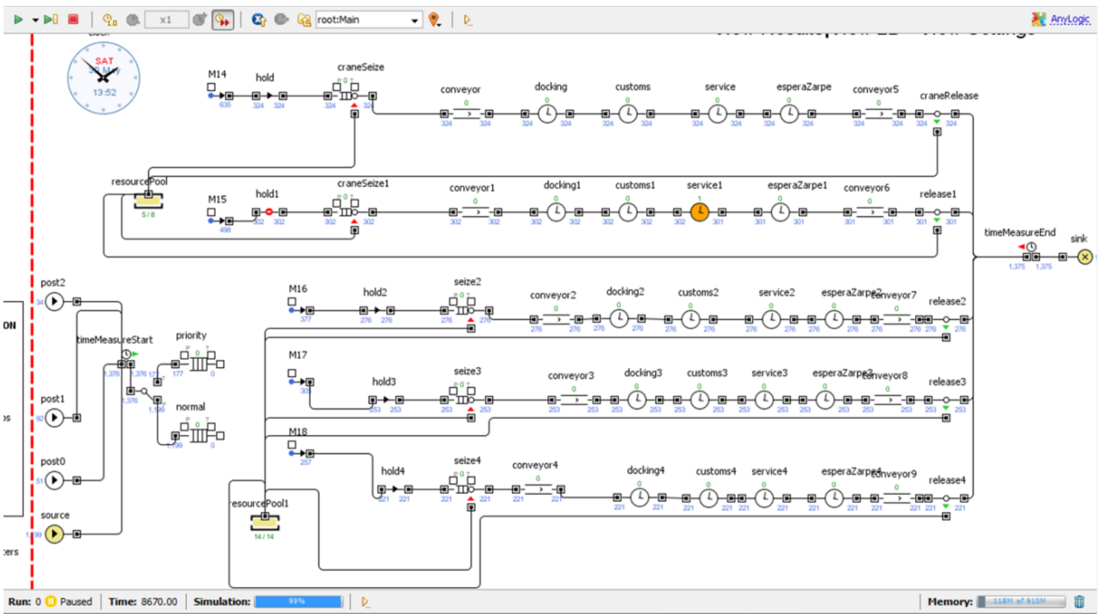


Figure 7-6: Berthing Process Simulation Model

A discrete event type of simulation model was deemed the most appropriate to model the gate subsystems. Discrete event modeling has proven to be beneficial in modeling of a wide variety of problems in transportation, manufacturing and logistics. As noted in Table 7-1, the Anylogic simulation platform was used to model the import and export process discrete event models. Real world data was used to feed the model (number of resources, interarrival times, and service times) and proper statistical analysis was done to validate the simulation models.

The different subsystems of the gate system (Precheck, Gatehouse and Lane) are divided into different discrete event process in the model. Each of the different gate system processes were modeled in the discrete event system as sub-process flows with all its associated process and time elements (queues, servers/delays, service logic when required) to represent the gate system data collected. Figure 7-7 illustrates the discrete event simulation model for the gate operations at the Port of Balboa.

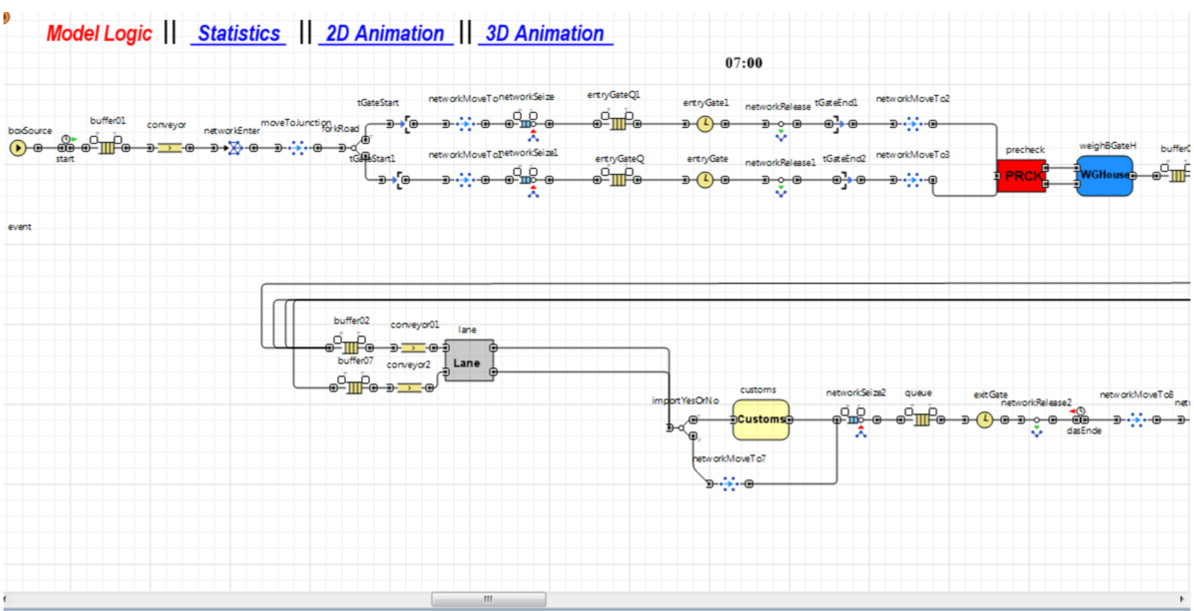


Figure 7-7: Gate Operations Simulation Model

The carbon footprint model is a continuous simulation model developed in AnyLogic using the system dynamics modeling technique to measure the Greenhouse gas (GHG) emissions that originate from the delivery of cargo load containers. Carbon dioxide (CO2) and nitrous oxide (N2O) emissions are calculated by this model. The range of the container vessels size is from 4,500 TEU to 12,000 TEU. The Carbon Footprint model for calculating CO2 and N2O emissions is shown in the Figure 7-8 below.

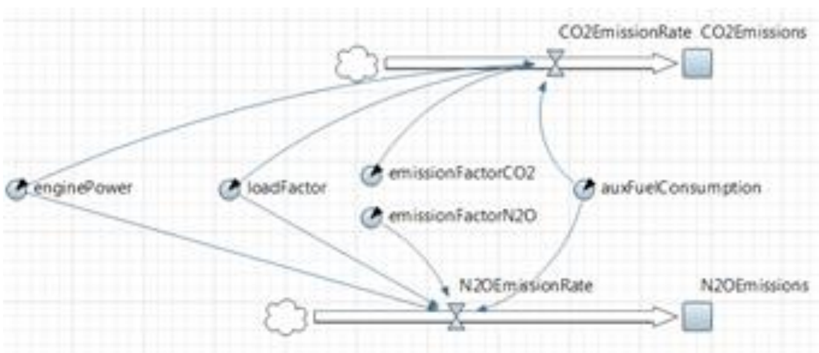


Figure 7-8: Carbon Footprint Emissions Model

Finally, a visualization federate was created using the SimiGon virtual simulation platform. Figure 7-9 illustrates some screenshots from the visualization federate. The virtual platform allows for terminal operation center personnel to performed visual inspection of the berth and gate operation at the port.

Figure 7-9: Visualization Model Screenshots

7.4 Case Study Summary

This case study was used to exercise the distributed and hybrid simulation developmental roadmap for the Port Maritime Operations at the Port of Balboa (Panama). The use of the MAK RTI 4.2 implementation of the HLA standard for distributes simulation systems enable the simulation model interoperation and experimentation. The roadmap is a preliminary work that provides guidance in the development of distributed and hybrid simulation systems. A more formal approach methodological framework can be developed in future work. Further, MBSE executable architecture capabilities shall be evaluated and tested to define a more sophisticated simulation framework.

CHAPTER 8. CASE STUDY #2 – MILITARY WAR FIGHTING SCENARIO

8.1 Case Study Introduction

This case study presents an experimental military war fighting example in which blue forces “Air Forces” and red forces “Ground Forces” are to engage in combat in a distributed simulation scenario. Proper terrain coherency and simulation entities interoperation is required during red and blue forces combat interactions in the distributed war fighting scenario. Distributed simulation systems and associated industry standards have their origin in the defense industry. Thus, military war fighting distributed simulation systems have been implemented across all the branches of the armed forces (marines, air force, navy and army) in the U.S. and other countries for war fighting scenario analysis and military personnel training purposes. The experimental military war fighting example described in this case study is presented to exercise our developmental roadmap and show its application capabilities for the proper architecting and implementation of distributed and hybrid simulation systems. Throughout this case study our distributed and hybrid simulation developmental roadmap guidelines and recommendations will be presented.

8.2 Military War Fighting Scenario Description

This experimental military war fighting example main objective is to provide military personnel trainees with a “Virtual” and “Constructive” (VC) distributed simulation system. Blue forces “Air Forces” and red forces “Ground Forces” are to engage in combat in a distributed simulation scenario. The implementation of the distributed simulation environment is being developed using the HLA/RTI distributed systems standard which will allow the interaction of the “Blue Forces” federate with the “Red Forces” federate. Phase 1 guidelines in our roadmap were applied to the war fighting scenario and details are included in Table 8-1.

Table 8-1: Case Study #2 – Phase 1 Roadmap Simulation Requirement Details

Items	Description
Objectives	Proper terrain coherency and interoperation between Red and Blue Forces in a distribute simulation environment Virtual simulation capabilities in the Blue and Red forces federate models Constructive simulation capabilities in the Blue and Red forces federate models
Number of Models	Helicopter /Virtual Simulation/Detail Helicopter /Constructive Simulation/Detail Surface to Air Missile (SAM)/Virtual Simulation/Detail M2 Hummer/Constructive Simulation/Detail
Type Models	Virtual Simulation/SIMbox by SimiGon Constructive Simulation/SIMbox by SimiGon
Level of Resolution	Detail

The "Blue Forces" simulation component (HLA federate) will be a combination of computer generated forces (CGF) entities (M2 Hummers) that will be defined at the constructive simulation level and a virtual surface-to-air missile (SAM) simulator. The "Red Forces" will be a VC simulation federate in the HLA/RTI distributed environment composed of a virtual Helicopter simulator and a CGF Helicopter CGF entity as well.

The virtual simulator components in the distributed simulation system provide the ability to model military systems and associated sub-systems that can be configured to convey realistic training environment and system operation experience to the trainees. Both virtual and constructive simulation components will be model using the SIMbox engine developed by SimiGon (www.simigon.com). The SIMbox engine implements the HLA/RTI through a middleware plugin to enable the distributed simulation model communications and interactions.

8.3 Blue and Red Forces VC Models Structure

The "Red Forces" are comprised of a virtual apache helicopter entity (AH-64) that is capable of providing a high-fidelity and realistic rotary aircraft simulation that can model systems and subsystem behaviors, including flight management systems, autopilot, and flight controls, etc. Further, any particular functional and/or behavioral characteristics of the apache helicopter that the systems modeler will like to configured to provide a more realistic training environment to trainees is possible with virtual simulators. In addition, the constructive simulation capabilities required for proper war fighting scenarios implementation can be executed with CGF entity task definitions. CGF entities can be set with automated behavior or Artificial Intelligence (AI) to configure entities to follow created routes and arrive at waypoints set and configured in the general war fighting scenario implementation. Phase 2 guidelines in our roadmap were applied to the Red Forces VC model and details are included in Table 8-2.

Table 8-2: Case Study #2 – Phase 2 Roadmap Red Forces VC Model Structure

Component	**Details**	**Items**	**MBSE Language/Diagrams**
Entities	Helicopter Virtual	Objects	SysML/BDD & Class
	Helicopter CGF	Objects	SysML/BDD & Class
Systems	Weapon	Process	SysML/Sequence & State
	Radar/Detection	Process	SysML/Sequence & State
	Navigation (flight controls)	Process	SysML/Sequence & State
	Fuel	Process	SysML/Sequence & State

"Blue Forces" Phase 2 implementation of our developmental roadmap and guidelines are shown in Table 8-3. The blue forces model structure includes a virtual surface-to-air missile (SA-8) simulator and four M2 Hummer CGF entities. SA-8 controls, weapon, fueling and other sub-system entities behavior and functional characteristics are implemented using the SIMbox simulation engine. The structures of the blue forces were determined to capture the appropriate level of abstraction to be implemented in the military war fighting scenario. MBSE modeling artifacts were specified in Table 8-3 according to the developmental roadmap guidelines to document and define the right level of decomposition and resolution of the simulation models.

Table 8-3: Case Study #2 – Phase 2 Roadmap Blue Forces VC Model Structure

Component	**Details**	**Items**	**MBSE Language/Diagrams**
Entities	SAM Virtual	Objects	SysML/BDD & Class
	M2 Hummer CGFs	Objects	SysML/BDD & Class
Systems	Weapon	Process	SysML/Sequence & State
	Radar/Detection	Process	SysML/Sequence & State
	Navigation (SAM controls)	Process	SysML/Sequence & State
	Navigation (driving controls)	Process	SysML/Sequence & State
	Fuel	Process	SysML/Sequence & State

MBSE modeling language and diagrams specified in this developmental phase enable simulation models structure definitions and their particular logical decompositions to meet the distributed simulation military war fighting scenario objectives. The blue and red forces VC simulation model objects and processes are the main modeling items to consider for describing the war fighting scenario in our distributed simulation system developmental efforts.

8.4 Communication Scheme and Data Structure of VC Models

Proper semantic and integration analysis is done thru Phase 3 and Phase 4 of our developmental roadmap. The simulation developmental roadmap enables the proper conceptual modeling approach to define the required number of attribute and parameters that will provide the means for an adequate interoperation between the different simulation models. The HLA standard provides all the necessary mechanism to define the appropriate type of information exchange between the models and also the right data exchange structure to safeguard proper interoperability in the simulation system.

Table 8-4: Case Study #2 – Phase 3 Roadmap Simulation Models Communication Details

Component	Details	Items	Standard	MBSE Language/Diagrams
Attributes	Altitude	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Speed	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Location	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Radio	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Weapon Type	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Damage Factor	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
Parameters	Kill Radius	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Armor Factor	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Frequency Type	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Fuel Rate	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Detection Range	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class
	Fire Range	individual	HLA 1.3, RPR-FOM 2.0	SysML/IBD, Parameter & Class

Table 8-4 illustrates Phase 3 communication scheme details for the blue and red forces VC simulation models attributes and parameters which are necessary for proper interoperation between simulation models. The HLA standard provides means for defining semantic structures that dictate what type of data is being exchanged between simulation objects in the distributed simulation environment. Also, the industry has defined a number of RPR-FOM data translation schemes for the different HLA standards (HLA 1.3, HLA 1516 and HLA 1516 evolved). In our case study the military war fighting distributed simulation scenario experimentation used the HLA 1.3, RPR-FOM 2.0.

Table 8-5: Case Study #2 – Phase 4 Roadmap Simulation Models Data Structure Details

Component	Details	Data Type	Standard	MBSE Language/Diagrams
Attributes	Altitude	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Speed	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Location	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Radio	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Weapon Type	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Damage Status	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
Parameters	Rate of Fire	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Damage Effect	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Radio Transmitting	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Fuel Quantity	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Track Range	enumerated	HLA/OMT	SysML/IBD, Parameter & Class
	Munitions Type	enumerated	HLA/OMT	SysML/IBD, Parameter & Class

As seen on Phase 3 of our developmental roadmap the types of objects and interactions that the red and blue forces can produce and consume are defined by the RPR-FOM 2.0 as defined by the HLA standard. However, Table 8-5 takes into consideration the HLA OMT standard to model the simulation “data exchange structure” of the VC simulation model objects, its attributes, the interactions and the interaction parameters to enable proper implementation of processes, states and operation between the simulation models in our experimental military war fighting distributes simulation scenario. Depending on the simulation engine capabilities and simulation paradigm OMT modification or syntactic modeling (or configuration) is required to enable the proper simulation interoperability between different simulation engines or platforms.

8.5 VC Models Construction and Experimentation

Our simulation development roadmap can support the analysis and development of distributed and hybrid simulation systems. The definition of complex war fighting scenarios can include the implementation of virtual and constructive (VC) simulation systems to accommodate training objectives for different levels of military personnel. Our "Red Forces" and "Blue Forces" war fighting scenario will be implemented using the HLA interoperability standard for distributed simulation systems. The implementation entails different hardware and software considerations to provide the adequate level of interaction, coherency and interoperability during the implementation of the VC simulation models.

Phase 5 of our developmental roadmap takes into consideration the simulation engines or platforms required to meet the overall simulation objects defined during the earlier phases of the roadmap. The HLA distributed simulation standard allows for proper configuration of different data types between the different simulation engines through an RTI middleware. Our roadmap takes into consideration industry available RTI middleware's to ensure proper architecting and implementation of the distributed and hybrid simulation system. VT MAK Technologies (www.mak.com) and Pitch Technologies (www.pitch.se) are some of the leading providers of RTI middleware for distributed simulation systems implementations. During phase 3 and phase 4 developmental efforts simulation models communication scheme and data exchange structure items were examined and using the HLA 1.3 and RPR-FOM 2.0 will meet all of our required and defined data exchange details for the HLA Federation.

The simulation construction Phase 5 of the developmental roadmap considers all the simulation model definitions done in the previous steps. Table 8-6 illustrates the Phase 5 roadmap simulation modeling engines for the Red and Blue forces war fighting scenario.

Table 8-6: Case Study #2 – Phase 5 Roadmap Simulation Modeling Engines

Simulation Type	Simulation Model	Simulation Engine	RTI Middleware	HLA Standard
Virtual	Helicopter (AH-64)	SIMbox	MAK RTI 4.2	HLA 1.3, RPR-FOM 2.0
	SAM (SA-8)	SIMbox	MAK RTI 4.2	HLA 1.3, RPR-FOM 2.0
Constructive	Helicopter (AH-64)	SIMbox	MAK RTI 4.2	HLA 1.3, RPR-FOM 2.0
	M2 Hummer	SIMbox	MAK RTI 4.2	HLA 1.3, RPR-FOM 2.0

The virtual simulator models were constructed using the SIMbox simulation engine developed by SimiGon (www.simigon.com). SIMbox is a simulation software platform capable of providing distributed simulation solutions for defense and civilian applications. SIMbox concept is the set of development tools for components based design and creation. SIMbox uses solution software for content creation, simulation, visualization, human machine interface and graphics modeling tools. SIMbox contains several software modules empowering users or developer in creating new contents and environments.

With the developed MBSE modeling artifacts the simulation construction can be executed. The virtual AH-64 simulation model was developed with the SIMbox Software Development Kit (SDK). The SIMbox SDK provides three object component types: The Logic Object Component (LOC), the Console Object Component (COC) and the Output Object Component (OOC) which are basic system components of all simulation entities in the SIMbox.

LOC is responsible for an entity's behavior such as steering and motion. COC is responsible for an entity's internal display. OOC is responsible for entity's external output. Table 8-7 provides a general overview of the definitions and the responsibilities of each object component in SIMbox for the development of the virtual simulator.

Table 8-7: SIMbox Object Component Types and Description

Type	Definition/Responsibility
Logic Object Component (LOC)	• Logical state of the system • Entity's behavior (flight motion) • Exposing the state as attributes(Token) • Responding to action calls • Initializing properties • For example, a fuel system LOC might expose a fuel level attribute that decreases over time
Output Object Component (OOC)	• Entity's external output (show after burner, move gears, play sounds) • External visual elements, such as external subparts • Managing the control of entity sounds. • For example, a fuel warning sound will play when the fuel-low attribute is set to true
Console Object Component (COC)	• Entity's internal display (speed indicator, altitude, fuel indicator) • Rendering visual elements inside the console and to reflect the system state as a response to attribute change callbacks • For example, a fuel gauge will respond to the fuel level attribute change and reposition the gauge needle

Figure 8-1 illustrates the SIMbox Toolkit environment for virtual entity development. All the LOC, COC and OOC object components required for proper functional behavior of the AH-64 virtual model can be done with the SIMbox Toolkit and the C++ software development kit (SDK) environment. The Microsoft C++ Visual Studio 10 is required to interface with the

SIMbox SDK and make modifications to existing object components or define new ones. The interface is a C++ class that inherits from the SIMbox object component base class in the Visual Studio 2010 environment.

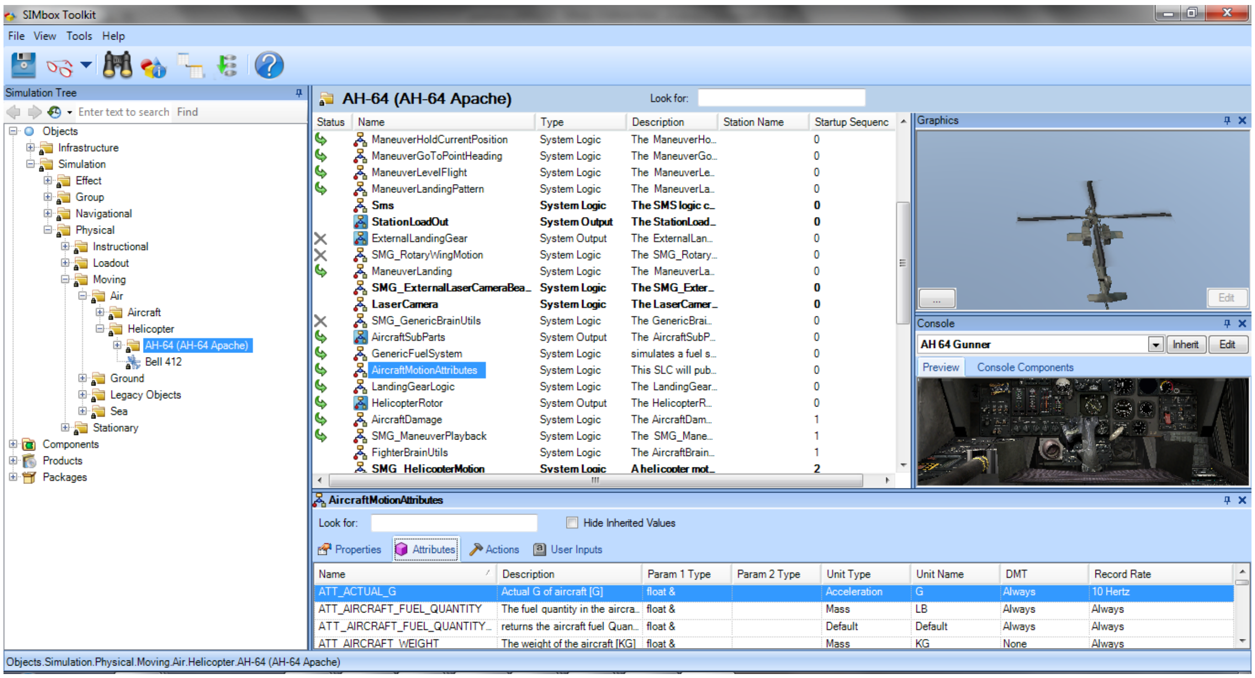


Figure 8-1: SIMbox Toolkit AH-64 Virtual Entity Definition Environment

The Red force AH-64 virtual simulation model can be seen in Figure 8-2. The virtual entity is a high fidelity model that accommodates all of the required entity attribute and parameters defined during the earlier phases of the developmental roadmap to provide the right level of interaction between other virtual entities (i.e., SA-8) in the scenario and CGF entities as well. The SIMbox engine allows the implementation of automated behaviors for CGF entities utilizing the LOC, COC and OOC object components. The AH-64 CGF entity definition was required to complete the Red forces composition.

Figure 8-2: AH-64 Virtual Simulator Screens

The Blue forces model structure included a virtual surface-to-air missile (SA-8) simulator and four M2 Hummer CGF entities. The SA-8 is low-altitude, short-range tactical SAM system. The simulator provides emulations of a range of SAM system engagement radar consoles. The simulation user and/or developer can modify or add the parameters representing SAM features. Figure 8-3 illustrates the partial SIMbox object composition of the SAM simulator architecture. The SIMbox engine can model the weapon dynamics, radio communications, radar detection and other entity functionalities to accommodate the requirements defined in the earlier developmental phases of our roadmap. Figure 8-4 illustrates the SA-8 virtual simulator developed with the SIMbox engine.

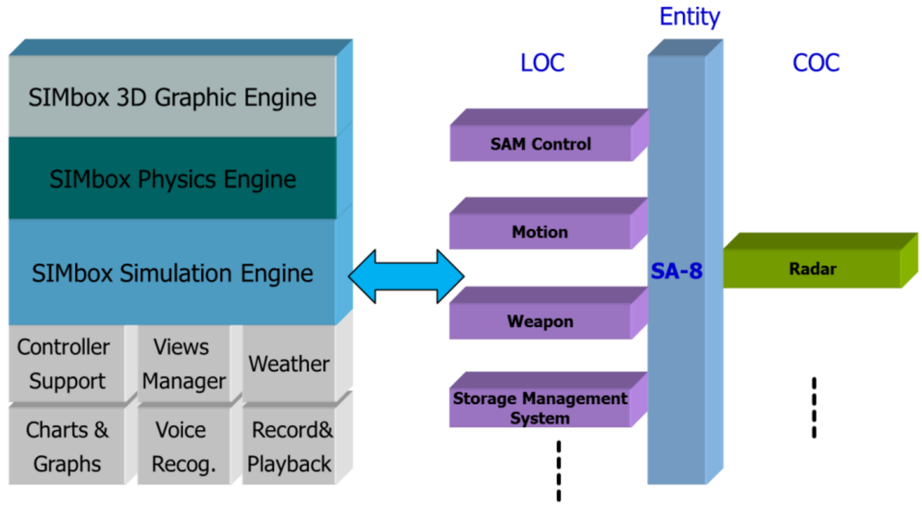


Figure 8-3: SA-8 Partial SIMbox Object Component Architecture

Figure 8-4: SA-8 Virtual Simulator Screens

Adequate interoperability and interactions between the virtual and constructive simulation components were implemented through the HLA 1.3 distributed simulation standard and using the “Real-time Platform-Level Reference” (RPR) federate object model version 2.0. The SIMbox simulation engine allows for HLA entities definition and interactions handling thru a “DisEntitiesMap” XML file that contains both generic translations as well as specific translations. Figure 8-5 depicts the default XML entities mapping scheme provided by the SIMbox simulation engine. New XML files with generic and specific entities mapping schemes can be created to implement the High Level Architecture (HLA) interoperability between the acting virtual and constructive simulation models in our distributed simulation military war fighting scenario.

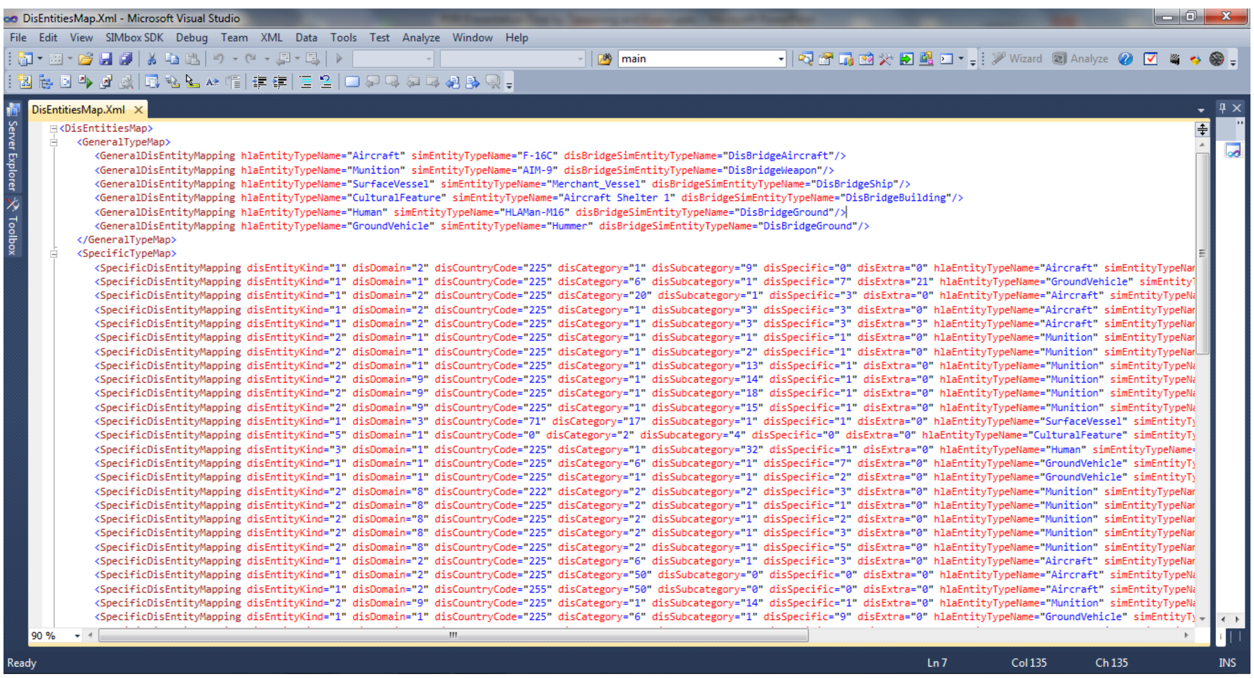


Figure 8-5: HLA Entity Mappings in SIMbox

Further, the SIMbox engine has a particular way to handle “Weapon Loadout Data”. The creation and deletion of weapon entities and their data handling and translation mechanism in the HLA distributed simulation environment are implemented similar to the Distributed Interactive Simulation (DIS) entity mapping required for the “SIMbox HLA Entities”. The weapon loadout properties that relate to the virtual or constructive simulation entities in the war fighting scenario have to be mapped to an XML file called “LoadoutAuxiliaryData.xml” in the SIMbox HLA content extension implementation as shown on Figure 8-6. The weapon “Loadout Auxiliary Data” is required for proper interoperability between simulation engines. The required HLA entity data mappings were implemented and adequate interoperation and the desired level of interaction between simulation environments were accomplished in our defined war fighting scenarios.

Figure 8-6: SIMbox Weapon Loadout Data Mappings

With the required RTI middleware HLA configuration in the SIMbox engine and VC simulation model building complete the experimentation between the Red and Blue forces federate simulation was implemented using the MAK RTI 4.2. Figure 8-7 illustrates the general configuration of the military war fighting HLA federation.

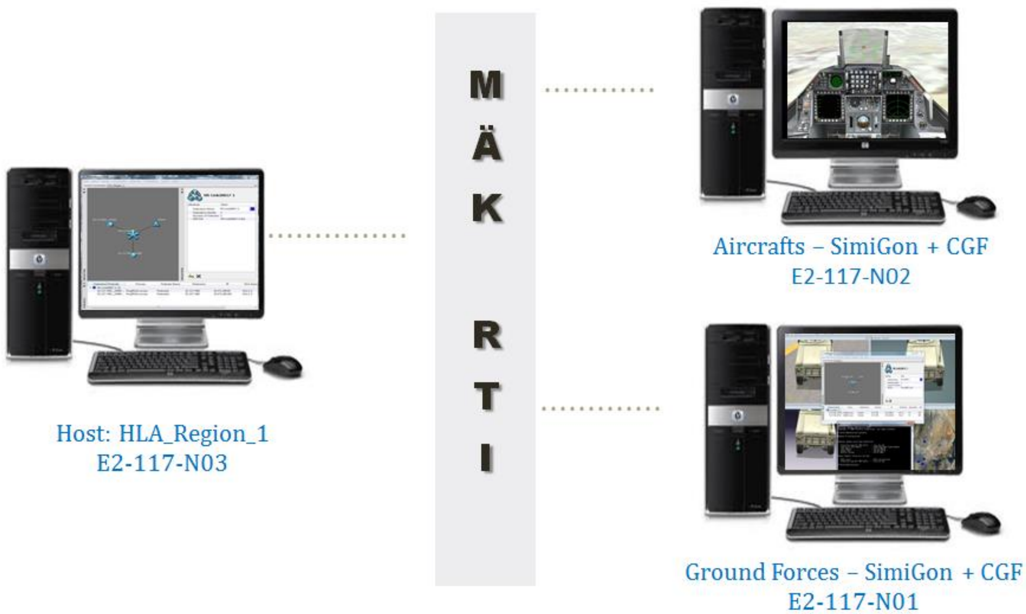


Figure 8-7: SIMbox Weapon Loadout Data Mappings

Three computer systems were utilized during our distributed simulation experimentation. An RTI host computer named E2-117-N03 was hosting the HLA_Region_1 with the MAK "Run-time-interface" (RTI) version 4.2. The other two computers were running the Red and Blue forces federate in our distributed simulation war fighting scenario. Figure 8-8 and Figure 8-9 illustrate the HLA Red and Blue forces joining the MAK RTI "VR-Link20017-1" federation.

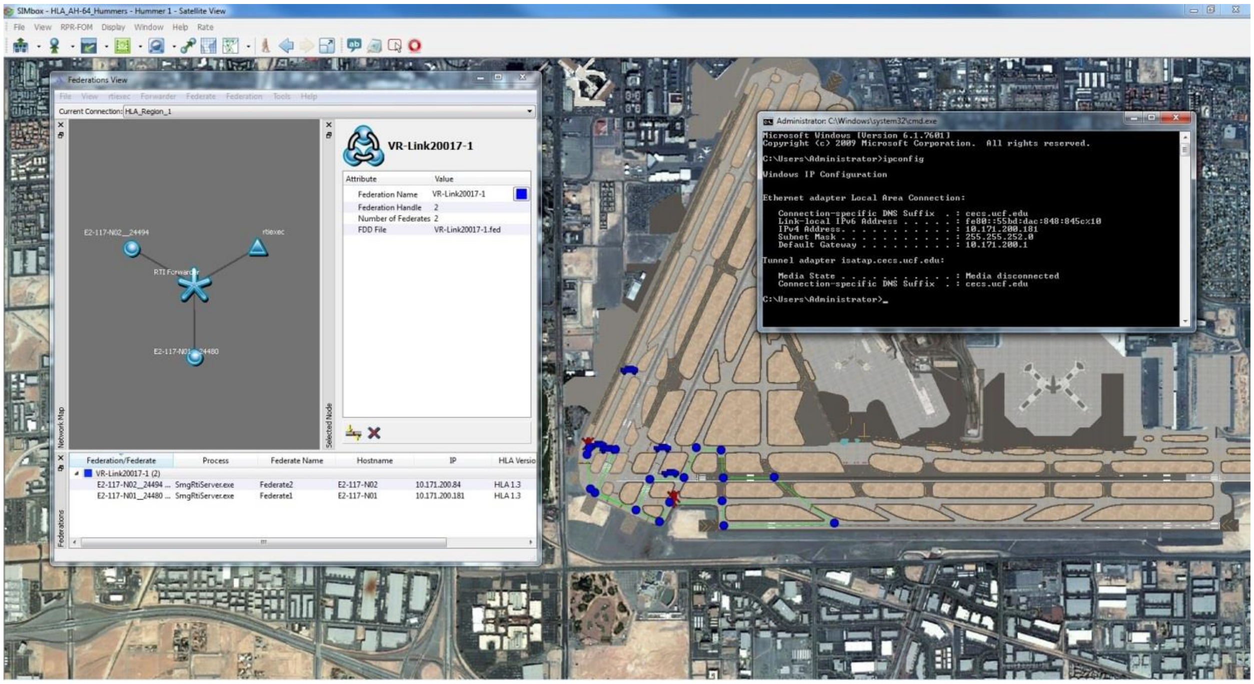


Figure 8-8: Blue Forces HLA Federate 1 Joining Federation “VR-Link20017-1”

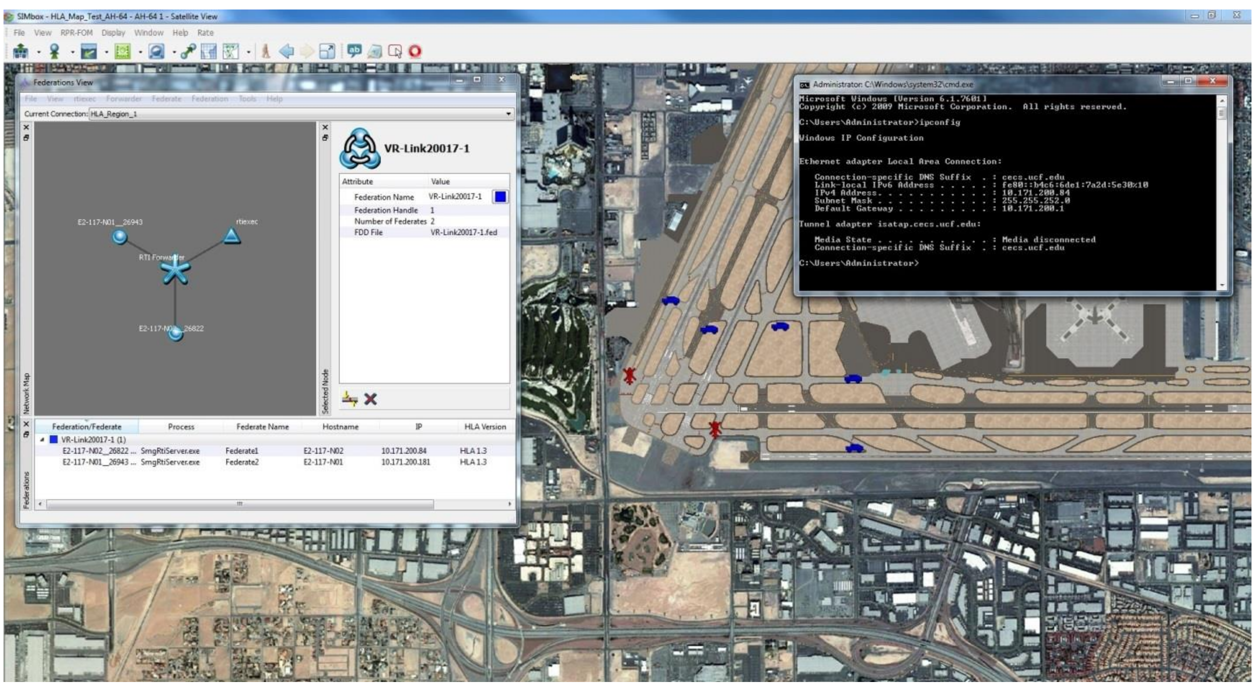


Figure 8-9: Red Forces HLA Federate 2 Joining Federation “VR-Link20017-1”

8.6 Case Study Summary

This case study was used to exercise the distributed and hybrid simulation developmental roadmap for the military war fighting simulation scenario experimentation. Blue forces “Air Forces” and Red forces “Ground Forces” successfully engaged in combat in a distributed simulation arrangement as described in this case study. The roadmap guidelines were carried out throughout the implementation of the war fighting military engagement scenario and the SIMbox simulation engine was used to implement the defined virtual and constructive simulation models. Our roadmap took into consideration the MBSE modeling artifacts that can be used to describe the simulation model, types and the overall distributed simulation arrangement. Our developmental roadmap is a preliminary work that can provide insight for a more formal modeling and simulation framework that can embrace the MBSE methods and tools for the successful architecture and design of distributed and hybrid simulation models.

CHAPTER 9. CONCLUSIONS, CONTRIBUTIONS AND FURTHER RESEARCH

9.1 Conclusions

This research examined the current practices of distributed and hybrid simulation systems applications in industry. Current distributed and hybrid simulation applications are more concern in their design and implementation and lack an integrated and systematic approach to initial analysis and functional requirements modeling as well as a holistic approach to the simulation lifecycle. Model building is all about providing the right level of abstraction about a particular real life situation and/or problem domain to enable some analysis. The roadmap for the development of distributed and hybrid simulation systems described in our research study spells out the recommended guidelines for development.

Conceptual modeling efforts also involve development of common definitions about a problem domain to enable the understanding of processes and objects that can describe a specific domain. A particular problem domain is not necessarily simple in structure. Meaning, a simulation model might need to be defined in a modular and hierarchical fashion to enable proper representation of a system or process. Simulation models can have different levels of complexity and conceptual modeling approaches can simplify the model building process. In general, conceptual modeling promotes and supports the reusability, interoperability and composability of simulation models.

MBSE can allow simulation engineers to formally model different aspects of a problem ranging from architectures to corresponding behavioral analysis, functional decompositions and user requirements (Jobe, 2008). Our research efforts included a survey study for collecting modeling and simulation (M&S) expert views, judgments and opinions regarding the capabilities and benefits of MBSE methods and tools for developing distributed and hybrid simulation systems.

The survey response data revealed that MBSE practitioners in the M&S domain found that MBSE requirement management and architectural system design capabilities and tools are beneficial during simulation system developments. This supports the notion presented by Garcia (2008) which notes that Model-Based System Engineering is "the practice and discipline within the field of system engineering that models system interactions and interoperability in order to better engineer or develop an intended system design" (p. 63). System interactions and interoperability characteristics are essential in the definition and implementation of distributed and hybrid simulation systems. These characteristics should to be taken into consideration throughout the entire system development cycle.

Wang (2009) expressed that proper interoperability is achieved when technical structures are closely aligned with the conceptual ideas. Thus, a top-down approach is necessary during development of distributed and hybrid simulation systems starting with conceptual modeling. The roadmap description and development in our research study emphasized on conceptual modeling and interoperability characteristics for the successful development of system requirements and design concepts of distributed and hybrid simulation development throughout their entire system lifecycle.

9.2 Contribution to the Body of Knowledge

This work has contributed to the distributed and hybrid simulation systems development community and the application of conceptual modeling principles with MBSE methods and tools. A well-structured process has been developed through a roadmap that takes into consideration MBSE modeling techniques that will allow proper architecting, functional decomposition and simulation system requirement definitions in support of a lifecycle management and implementation of distributed and hybrid simulation systems.

A single or individual simulation approach to the ever increasing complexity of business enterprise processes today cannot be captured or analyzed by a single simulation and modeling paradigm. Not only capturing and modeling business process complexities for decision making is important. But understanding and managing the lifecycle of an entire distributed and hybrid simulation system design and implementation from cradle to grave is a challenge and should be of great importance as well. Our research survey study elicited MBSE practitioners in the modeling and simulation domain and the findings recorded in data analysis is also a contribution to the body of knowledge. Further research can leverage from our survey study findings and expand on the guidelines and our simulation development roadmap definition.

9.3 Directions for Further Research

We believe that our guidelines and roadmap definition has provided valuable insight and direction in the development of distributed and hybrid simulation systems development. However, we cannot claimed that our research study we have covered all the research areas in this domain. Conceptual modeling approaches will continue to be an interesting topic in the development of distributed and hybrid simulation systems. Formulating new approaches for conceptual modeling techniques will only enriched the effectiveness of interoperability characteristics in distributed and hybrid simulation systems.

Our of distributed and hybrid simulation systems developmental roadmap was implemented through a Port Maritime case study that demonstrated the capabilities of MBSE methods and tools to aid in simulation system developments. However, other complex systems domains can benefit from this roadmap as well. For example, drinking water and wastewater treatment systems are highly complex and could benefit from distributed and hybrid simulation systems experimentation. Water and wastewater facilities employ supervisory and control data acquisition systems (SCADAS) which are sophisticated instrumentation and control platforms that manage the application of complex water treatment technology processes. Training of water treatment plant operations is needed due to the attrition of operators. Expanding the simulation roadmap developed in our research study can prove beneficial in this domain.

In addition, our developed roadmap can support the multiresolution modeling (MRM) concepts. Currently, this particular modeling concept presents challenges in distributed and hybrid simulation system developments for the lack of a well-structure modeling process or approach. The multiresolution entity (MRE) and multiresolution families (MRF) MRM methods can benefit from the semantic and syntactic concepts in distributed and hybrid simulation systems. Advantages of using MBSE methods and tools shall also be explored in the context of MRM modeling techniques.

APPENDIX A: MBSE SURVEY INSTRUMENT

Introduction

Dear Participant,

You are being invited to take part in a research study. Whether you take part is up to you.

My name is John A. Pastrana (principal investigator), I am a PhD candidate in the University of Central Florida department of Industrial Engineering and Management Systems. I am conducting a survey,

"Model-Based Systems Engineering Approach to Distributed/Hybrid Simulation Systems"

We are NOT collecting any personal information. Just want to get the professional views, judgments or opinions of Modeling and Simulation professionals in terms of a Model-Base Systems Engineering (MBSE) approach to modeling and simulation (M&S) project development efforts.

MBSE languages, methods and tools are used for M&S project developments. We are interested in knowing to what level, from your experience, the use of requirement management database tools, model-based system engineering languages (for creating use-case, activity and sequence diagrams, etc.) and system architecture development tools for defining models and sub-models with executable simulation, trade-off analysis and automatic documentation capabilities have or could have benefited your M&S projects.

There are 22 questions and almost all of them are radio button choices (Agree/Disagree). It takes 10 minutes to complete. Comments are welcome.

You must be 18 years old to participate in this survey.

This survey is part of my dissertation main goal and/or contribution to the M&S community which aims at the definition of a methodological framework that uses MBSE languages, methods and tools for the development of Distributed/Hybrid Simulation Systems.

Thank you for your participation!

Should you have any questions or comments about the study or to report a problem:
Please contact,
Principal Investigator: John A. Pastrana,
Graduate Student (pastranaja@knights.ucf.edu)
UCF Industrial Engineering and Management Systems

Faculty Advisor: Dr. Luis Rabelo,
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Tel. (407) 882-0091

IRB contact about your rights in the study or to report a complaint: Research at the University of Central Florida involving human participants is carried out under the oversight of the Institutional Review Board (UCF IRB). This research has been reviewed and approved by the IRB. For information about the rights of people who take part in research, please contact: Institutional Review Board, University of Central Florida, Office of Research & Commercialization, 12201 Research Parkway, Suite 501, Orlando, FL 32826-3246 or by telephone at (407) 823-2901.

1. During your recent modeling and simulation projects which type of model-base systems engineering (MBSE) methods and tools have you used from the list below? Check all that apply or specify other.

- ☐ IBM Telelogic Harmony SE
- ☐ INCOSE Object-Oriented System Engineering Method (OOSEM)
- ☐ IBM Rational Unified Process for Systems Engineering (RUP SE)
- ☐ VITECH Model-Based System Engineering (MBSE) Methodology
- ☐ JPL State Analysis (SA)
- ☐ DORI Object-Process Methodology (OPM)
- ☐ Artisian Studio Tools
- ☐ IBM Rapshody
- ☐ SparX Enterprise Architect
- ☐ IBM Rational RequisitePro
- ☐ IBM Telelogic DOORS
- ☐ Other

Other (please specify)

MBSE Methods and Tools for Requirements Management

We would like your opinion regarding the use of MBSE methods and tools for system requirement definition and management throughout the entire developmental lifecycle of your recent M&S projects. Interoperability implementation in distributed/hybrid simulation systems is an important developmental concept in M&S systems. The following questions explore which are the most appropriate aspects of MBSE methods and tools that enable better requirement management and definitions.

2. During your recent modeling and simulation projects which type of model-base systems engineering (MBSE) languages have you used from the list below? Check all that apply or specify other.

- ☐ UML
- ☐ SysML
- ☐ BPMN
- ☐ IDEF0
- ☐ AADL
- ☐ OPL/OPD (OPM)
- ☐ Other

Other (please specify)

3. From your experience, to what level would you agree or disagree that MBSE languages (e.g., UML, SysML, IDEF0, etc.) contribute to the successful definition of system requirements of your M&S project?

○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree

Any comment/opinion regarding this question?

4. From your experience, to what level would you agree or disagree that MBSE languages (e.g., UML, SysML, IDEF0, etc.) contribute to the successful communication of system requirements to the client and other team members in your M&S project?

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Any comment/opinion regarding this question?

5. From your experience, to what level would you agree or disagree that MBSE tools with requirements definition and management (e.g., traceability) capabilities contribute to the successful communication of system requirement to the client and other team members in your M&S project?

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Any comment/opinion regarding this question?

6. From your experience, to what level would you agree or disagree that MBSE tools with requirements trade-off analysis capabilities contribute to the successful communication of system requirement to the client and other team members in your M&S project?

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Any comment/opinion regarding this question?

7. During your recent modeling and simulation projects to what level would you agree/disagree that MBSE system modeling methods and tools have:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Increased your personal productivity	○	○	○	○	○
Increased the productivity of the development team	○	○	○	○	○
Made it easier to define and maintain your M&S projects requirements	○	○	○	○	○
Contribute to the overall project successful implementation and validation of the system requirement process	○	○	○	○	○

Any comment/opinion regarding this question?

MBSE Methods and Tools for Systems Architecture and Design Development

We would like your opinion regarding the use of MBSE methods and tools for systems architecture and design efforts throughout the entire developmental lifecycle of your recent M&S projects. Interoperability implementation in distributed/hybrid simulation systems is an important developmental concept in M&S systems. The following questions explore which are the most appropriate aspects of MBSE methods and tools that enable better systems architecture and design development.

8. From your experience, to what level would you agree/disagree that MBSE tools for automatic generation of system modeling diagrams (e.g., use case diagrams, activity, sequence, etc.) have or could have contributed to the successful definition of system design and functional architecture of your M&S project?

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

Any comment/opinion regarding this question?

9. From your experience, to what level would you agree/disagree that MBSE tools for automatic generation of architectural and design documentation have or could have contributed to the successful definition of the system architecture and design (i.e., functional, physical, and/or behavioral architecture) of your M&S project?

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

Any comment/opinion regarding this question?

10. From your experience, to what level would you agree/disagree that MBSE tools with an executable simulation capability have or could have contributed to the successful definition and implementation the system architecture and design (i.e., functional, physical, and/or behavioral architecture) of your M&S project?

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

Any comment/opinion regarding this question?

11. From your experience, to what level would you agree/disagree that MBSE software programming language code generation tools (e.g., C, C++, Java, etc.) have or could have contributed to evaluation and/or testing of the system architecture and design (i.e., functional, physical, and/or behavioral architecture) of your M&S project?

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

Any comment/opinion regarding this question?

12. During your recent modeling and simulation projects to what level would you agree/disagree that MBSE with automation capabilities (e.g., code generation, automated documentation generation, and executable simulation) for system architecture and design (i.e., functional, physical, and/or behavioral architecture) have or could have:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Increased your personal productivity	○	○	○	○	○
Increased the productivity of the development team	○	○	○	○	○
Made it easier to define and develop your M&S system architecture and design	○	○	○	○	○
Contribute to the overall project successful implementation and validation of the system architecture and design	○	○	○	○	○

Any comment/opinion regarding this question?

Systems Development Experience and Professional Role

As indicated earlier, no personal information is being collected. We just want to quantify the experience of modeling and simulation professionals participating.

13. About how long have you been involved in Modeling and Simulation systems development?

- 0-5 years
- 5-10 years
- 10-15 years
- 15-20 years
- >20 years

14. Which of the following best describes your current systems development role in M&S projects?

- Systems Engineer
- Systems Developer
- Systems Modeler
- Systems Architect
- Team Leader
- Project Manager
- Domain Expert - Specialist
- Systems Testing
- Systems Validation

Any comment/opinion regarding this question?

15. How long have you been in your current systems development role?

- 1-2 years
- 2-5 years
- 5-10 years
- 10-15 years
- >15 years

16. Which of the following best describes your organization?

- Academic
- Industry
- Goverment

17. Which of the following best describes the principal industry of your organization?

- Aerospace
- Defense
- Automotive
- Finance & Financial Services
- Manufacturing
- Telecommunications
- Energy
- Space Systems
- Other

Other (please specify)

18. Approximately how many employees are there in your company or organization?

- 1 -10
- 10 -100
- 100 -1000
- 1000 - 10000
- > 10000

19. In which areas of system development have your organization use MBSE languages, methods and tools for Modeling & Simulation projects? Check all that apply and specify other.

- ☐ Requirements Management
- ☐ System Design
- ☐ System Validation
- ☐ Executable Models / Simulation
- ☐ Verification Planning / Test Execution
- ☐ Trade-off Studies
- ☐ Code Generation
- ☐ Other

Other (please specify)

20. From your experience, to what level would you agree/disagree that MBSE languages, method and tools have or could have help your Organization to support and maintain M&S projects throughout the entire development lifecycle?

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

Any comment/opinion regarding this question?

21. From your experience, to what level would you agree/disagree that MBSE languages, method and tools have or could have help your Organization to respond faster to new client implementation requirements and/or business opportunities?

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

Any comment/opinion regarding this question?

Final Comments

Any final comments regarding the survey or your participation are welcome in the space provided below. If you wish to find out the results of this survey please email us to the contact email at the bottom of the recruitment email. Thank you for your participation!!!

22. Any questions/comments regarding your participation?

APPENDIX B: IRB APPROVAL LETTER OF EXEMPT HUMAN RESEARCH

University of Central Florida

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Exempt Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **John Pastrana**

Date: **July 10, 2014**

Dear Researcher:

On 7/10/2014, the IRB approved the following activity as human participant research that is exempt from regulation:

Type of Review:	Exempt Determination
Project Title:	Model-Based Systems Engineering Approach to Distributed and Hybrid Simulation Systems
Investigator:	John Pastrana
IRB Number:	SBE-14-10410
Funding Agency:	
Grant Title:	
Research ID:	N/A

This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these changes affect the exempt status of the human research, please contact the IRB. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Kanielle Chap

IRB Coordinator

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