VISUAL AND PERSISTENT

CO-DESIGN MODELING FOR NETWORK SYSTEMS

by

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ABSTRACT

Network systems are challenging to model because of the complexity inherent in the software and hardware designs as well as the numerous ways that they may be synthesized. A desired goal towards describing computer network systems is: visual and persistent modeling of combined software and hardware components. Furthermore, the co-design modeling approach is poised to provide advanced capabilities to support separate and combined specifications of software and hardware layers of network systems.

The Distributed Object Computing (DOC) approach offers an abstraction for modeling any network system in terms of logical specification of software and hardware components and the mappings of the former to the latter. The abstraction defines software (Distributed Cooperative Objects (DCO)), hardware (Loosely Coupled Network (LCN)), and Object System Mapping (OSM) models. These models can be described and simulated in DEVS/DOC – a DEVS-based environment for simulating DOC models. However, neither DOC nor DEVS offers visual and persistent model concepts and methods. In contrast, Scalable Entity Structure Modeler (SESM) framework supports a unified logical, visual, and persistence component-based model development for specifying families of complex system designs, but it lacks direct support for co-design.

Considering the limitations of DEVS/DOC, SESM, and other modeling approaches, this dissertation develops an approach called SESM/DOC where logical co-design model specifications can be developed visually and stored in relational databases. This approach introduces visual and persistent co-design capabilities for describing a family of logical models for network systems. The SESM/DOC has been devised to

support consistent logical, visual, and persistent modeling for the DCO, LCN, and OSM models. A prototype has been developed *(i)* to support separate visual working sections for software and hardware modeling and their synthesis, *(ii)* to store logical co-design models, and *(iii)* to automatically generate partial equivalent DEVS/DOC models. For the purposes of demonstration, an example of search engine systems is considered. The example is modeled in SESM/DOC and simulated in DEVS/DOC. The role of the proposed co-design modeling approach and its application for development of network system designs is examined and select future research directions are briefly described.

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TABLE OF CONTENTS

Page

LIST OF TABLES

TABLE OF FIGURES

1 INTRODUCTION

1.1 The Problem

Networks of computer hardware and software systems have grown rapidly in their complexity and scale due to advances in computer science and software engineering. Examples of such systems are search engines, global information systems, and command and control engineering enterprises. These systems are complex and are stretching the capabilities of the most advanced analysis and design approaches and their state-of-the-art tools.

Integral to building such systems is the desire to increase the performance-to-cost ratio. A key phenomenon is the continuing shift from central computing technologies to their distributed counterparts. One aspect of these modern network systems is that their highly intricate dynamics are rooted in architectural design choices, constraints, and the technologies that are used to build them. The difficulties of designing a large-scale and complex network system (e.g., an enterprise system supporting large-scale distributed event processing in the domain of information management) provide challenging research questions for simulation-based system modeling. Developing solutions to these questions is considered important fundamental research with key implications in the engineering of network systems for commercial and government uses.

Another aspect of a modern network system is that software components may be mapped onto alternative networked hardware components. Therefore, a basic concept in computer-aided system design is to distinguish between software and hardware

components while allowing the flexibility to synthesize these different components to create the desired system architectures.

To create network systems and in particular support simulation-based system design, it is advantageous to bring together concepts, methods, and practices from modeling and simulation, software engineering, and system engineering. Modeling and simulation has been widely applied in system engineering which provides an overarching framework for defining, developing and deploying systems (Sage & Armstrong, 2000). Analysis and design are essential parts of system engineering as well as software engineering. Today's system engineers must handle systems that are by orders of magnitude more complex than those they could deal with just a few years ago. In order to develop design and analysis models for network systems, a system has to be decomposed hierarchically into its comparatively simpler sub-systems (or components). Intelligent decomposition of a system is prerequisite to success in developing network systems. Furthermore, the design of the individual components is generally difficult. Decomposition of a system into a set of cohesive software and hardware components remains challenging for scientists and engineers. Similarly, it is difficult to select and fit a component appropriately into a system's architecture. The structure and behavior of the components of a system affect the overall system and, conversely, the structure and behavior of the system influences the choices of the components.

The above problems are conceptually similar to those that have been considered for embedded systems. To allow combined model-based software and hardware design, the concept of co-design was developed. It allows designers to simultaneously account

for requirements that span to both the software and to the hardware on which the software is expected to execute. Embedded systems have their own unique requirements but also share some basic concepts with those of distributed network systems. The separation of embedded software and hardware and the successful application of co-design offer a strong case for their use in architecting network systems. Indeed, a co-design methodology has been developed for simulation-based analysis and design of systems. The approach supports system architects in simulation and to in evaluation of design choices. Engineers can try different designs with the convenience and systematic use of co-design simulation models that separate and integrate software and hardware parts of systems. Enabling the design of network systems, however, requires co-design capabilities that are rigorous and simple to use.

1.2 Current Approaches and Challenges

Engineering of the above network system architectures is of interest to analysts and designers alike. System architects must deal with the complexity of network systems and the limitations of existing modeling approaches from both software and simulation design perspectives. To overcome the restrictions and inadequacies of techniques and methods for describing a system's structure and behavior, researchers are pursuing solutions that can simplify system design, such as system modeling and simulation.

A model is a set of instructions, rules, equations, or constraints to present the structure or behavioral properties of a system (Blanchard, 2004). Simulation makes one system (model or models) do the essential work of another system. There are many

reasons for using modeling and simulation in system design (Wymore, 1993). Modeling and simulation play an important role before the system is built, while the system is being built, and after the system is completed. For large-scale and complex systems, modeling and simulation is particularly important because testing these kinds of real systems is often not possible and/or is expensive. One school of research is primarily interested in software and system modeling such as MDD (Model-Driven Design) (Muth, 2005), UML (Object Management Group, 2007), Service Oriented Architecture (Anand, Pandmanabhuni, & Ganesh, 2005), Grid Computing (Darema 2005), SysML(Hause, Thom, & Moore, 2005), and Raphosady (Gery, Harel, & Palachi, 2002). Another school of research is pursuing simulation-based approaches with strong emphasis on developing models that can be simulated dynamically, such as SMART (simulation and modeling for acquisitions, requirements, and training) (Lunceford, 2002), and DEVS (Discrete Event System Specification) (Sarjoughian & Cellier, 2001; Zeigler, Praehofer, & Kim, 2000). Some of these approaches are advocating developing simulation models that can be mapped (semi-)automatically to specifications that can serve as blueprint for engineering the real systems (Godding, Sarjoughian, & Kempf, 2007; Hu & Zeigler, 2005). More broadly, it is important to develop suitable modeling frameworks, processes, and tools that enable modelers to describe a family of network system designs and evaluate their static and dynamic aspects during concept and architecture development phases of system engineering. Such capabilities are indispensable in engineering network systems that could have alternative architectures based on requirements that are generally not unique.

The scalability and complexity of modern systems force system engineers to rely increasingly on modeling and simulation technology (Zeigler, Praehofer, & Kim, 2000). To support analysis tradeoffs amongst competing architecture designs and the requirements posed by customer and users, models can be developed and in some cases simulated (Davis & Anderson, 2004; Johnson & Mckeon, 1998; National Research Council, 2002; Schmidt, 2006). Simulation modeling is often the only means by which the inherent system complexity can be studied in a dynamical setting.

It is important to note that separation of software and hardware components has been studied for many years in the context of embedded systems (Graaf, Lormans, & Toetenel, 2003; Lee, 2000; Olson, Rozenblit, & Jacak, 2007; Rozenblit & Buchenrieder, 1995; Seo, Lee, Hwang, & Jeon, 2006). In particular, modeling and simulation methods and tools (Bai & Dey, 2001; Herzen & Lerer, 2006) have been developed to describe and simulate systems on chips. More recently, modeling and simulation has been proposed to aid design and performance analysis for distributed computing systems (Butler, 1995; Hild, 2000; Hild, Sarjoughian, & Zeigler, 2002; Sarjoughian, Hild, & Zeigler, 2000).

There are many modeling approaches; some of which are general-purpose while others are tailored for specific domains. Some support logical modeling while others also support visualizing models or offer simple means for constructing model structures or specifying basic behavior. A number of tools have been developed for simulating networks among which are NS-2 (Information Sciences Institute, 2004), OPNET (OPNET Technologies, 2004) , and QualNet (Jaikaeo & Shen, 2005).

Among the above modeling approaches and tools, Scalable Entity Structure Modeler (SESM) and DEVS/DOC are of particular importance in this work. SESM offers a unified logical, visual, and persistent modeling framework (Fu, 2002; Sarjoughian, 2005; Sarjoughian, 2007). It provides a unified foundation for describing alternative hierarchical logical models of systems with direct support for visual modeling and persistent model storage. The logical models can be transformed to partial source code (Bendre & Sarjoughian, 2005) and the structural complexity of models stored in the repository can be measured (Mohan, 2003). Models can be specified using decomposition and specialization with coupling to synthesize hierarchical models in a modular fashion. A key aspect of SESM is to support large-scale design models visually and support reuse of models using a persistent model database. However, it does not inherently support co-design – i.e., separating software and hardware and integrating them to describe network systems.

Distributed Object Computing (DOC) is defined as a set of abstract models describing the software layer/hardware layer and their mapping (Butler, 1995). DOC provides the concepts for logical co-design specification of Distributed Cooperative Object (DCO), Loosely Coupled Network (LCN), and Distributed Cooperative Object (DCO), and the Object System Mapping (OSM) between them. DEVS/DOC introduces the concept of simulation modeling by developing a concrete, formal specification of the abstract DOC models and implementing a suite of software and hardware components in DEVSJAVA (Hild, Sarjoughian, & Zeigler, 2002; Hu & Sarjoughian, 2005). It supports modeling and simulating DOC models in the DEVSJAVA environment. However,

DEVS/DOC does not support visual modeling and model persistence and thus measuring the structural complexity of systems. Instead, modelers are required to specify their models using the abstractions provided by DEVS and DOC and develop simulation code with Integrated Development Environments (IDE) such as Eclipse (Clayberg & Rubel, 2006). Given the strengths and limitations of SESM and DOC with respect to network system co-design, it is desirable to develop an approach where software and hardware models can be specified separately and systematically integrated.

Given the above brief overview of the current modeling and simulation approaches, there remain existing challenges for the co-design modeling of large-scale network systems as outlined below:

- How to design visual models for a distributed network system with respect to software and hardware parts. One important key to this is the visual modeling specifications for the separation of the network software model and hardware model, and the synthesis of the co-design (software/hardware) network.
- How to specify, organize and decompose a large number of network components so that the models can show different aspects of their relationship properties in a limited visual space.
- How to specify models for the network system to provide model reusability and management to a large number of models with regard to its software and hardware components. The specification of persistent co-

design models should not only support the separation of software and hardware models, but should also to support their synthesis.

- The different constraints from software and hardware components in a network system need to be enforced in co-design modeling. Any violation to these constraints in visual model design should be checked so that verification and validation can be performed for co-design modeling based on model constraints.
- The network system complexity should be measured for its software and hardware components, and also as an integrated system. The complexity measurement should include the quantity of models, model components, and the number of coupling relationships between the models.
- Partial co-design simulation models need to be generated from visual and persistent model design. The completed code should be simulated in a simulation environment so that the system model can provide analysis results with regard to the different software/hardware configurations.

1.3 Contributions

This dissertation provides a *visual* and *persistent co-design* modeling approach for specifying distributed network systems. A prototype environment is developed to implement this approach to help system engineers design large-scale and complex network systems with the *separation* and *synthesis* of system software and hardware components.

Compared with other modeling and simulation approaches such as UML, SMART, DEVS, etc., the visual and persistent co-design modeling approach provides a *layered structure* for network systems to specify the separation and synthesis of software and hardware components. Model styles are defined to support this layered structure modeling to help separate software and hardware aspects of a system and their configurable integration. The designed models are saved and managed in a database management system. *Constraints* from software and hardware components are specified and enforced. Different from other network system modeling and simulation frameworks such as NS-2, OPNET, QualNet, and DEVSJAVA; the developed prototype environment, SESM/DOC, provides a visual and persistent modeling approach and a set of *co-design working sections* for software/hardware visual and persistent co-design. It provides both block structure and tree structure for visual model design and models are managed in a database instead of flat files. These working sections guarantee the separation of different model layers and provide the facility to perform the system integration. Early stage model verification and validation can be performed based on the enforced model constraints. System complexity can be measured and partial simulation code for software, hardware, and an integrated system can be generated.

A set of search engine network models are implemented in SESM/DOC following the visual and persistent co-design approach. Different design options are realized and models are analyzed with simulations to illustrate the capabilities to design different software and hardware and their configurable synthesis in a network system.

1.4 Dissertation Outline

In the following, a brief overview of each chapter is provided. In Chapter 1, we have discussed the problems and challenges that occur in modeling large-scale and complex network systems. We reviewed some relevant and important aspects of modeling and simulation, gave a brief discussion for related work, and outlined the contributions of this dissertation.

Chapter 2 begins with a background of system design and focuses on the role of modeling and simulation. Then, the system theory basis for modeling and simulation is presented. It describes why models can be used as representations of real or imagined systems. The system-theoretic framework provides foundational system morphisms and system formalisms. Some basic modeling concepts (logical model, visual model, persistent model, simulation model, and modeling verification and validation) which will be used in the proposed approach will be described in this chapter. In this dissertation, a software environment for modeling is proposed, so in this chapter a discussion about the relationship between software engineering and modeling and simulation is provided. Some popular modeling and simulation software tools are also examined in this chapter. This chapter concludes with model-driven engineering concepts.

In Chapter 3, the basic elements of the proposed SESM/DOC modeling approach and some of their implementations are introduced. These elements are SESM, Discrete Event System Specification (DEVS), and Distributed Object Computing (DOC) abstract models. DEVSJAVA, SESM/CM, and DEVS/DOC are realizations of DEVS, SESM

DEVS/DOC in the Java™ programming language. The account of these modeling and simulation elements provides a basis for SESM/DOC which is an extension of SESM and DOC. DEVSJAVA is important because it is used for supporting the development of DOC models in DEVS. The partial simulation model generated through SESM/DOC is specified in DEVS/DOC. A comparison of DEVS/DOC and other simulation tools is presented.

In Chapter 4, the SESM/DOC approach is introduced from the logical modeling perspective. The details of component-based software and hardware layered structure modeling are presented with consideration for the different model types that were devised for SESM. A simple network example is used to illustrate the basic aspects of specifying logical design of network systems and what is desired from a modeling tool perspective. Based on the distributed co-design system properties and the features of a desired distributed co-design modeler, details are presented that account for layered structure decomposition of a distributed computing system, the constraints in a distributed computing system, and the model bases that can support storage of logical software, hardware, and their combinations. The distributed co-design system model types and the constraints related to these different model types are described. Finally, there is a discussion about describing SESM/DOC models.

In Chapter 5, visual modeling and persistent modeling are introduced. Described here are the concepts of model working sections where a modeler is provided with visual models to develop the DOC, LCN, or OSM model. The integrated input and output ports, bidirectional coupling and multiple-model tree structures are devised to support visual

co-design modeling. For the co-design model repository, specialized database schemas for DOC, LCN, and OSM models are developed and described.

In Chapter 6, a search engine network example is developed to illustrate model development in SESM/DOC. First, the modeling of search engine networks is considered. Second, the hardware models, software model, and integrated system models are developed sequentially to illustrate how distributed hardware and software aspects as well as the combined software/hardware network system can be modeled. Third, it is shown how a family of models can be developed with specialized models; and thus enabling the design of alternative model candidates systematically. Fourth, the SESM/DOC modeling supporting for adding state variables, obtaining complexity metrics, and generating partial simulation code is discussed. Fifth, the V&V issue is addressed and partial code generation is presented. Finally, different network models (e.g., same software model with different network hardware topologies and configurations, same network hardware with different software configurations) are simulated and evaluated in terms of scalability and performance traits.

In Chapter 7, a comparison of SESM/DOC is made and the importance of supporting co-design modeling for network systems is summarized. This includes the key aspects of the SESM/DOC co-design modeling such as separation of software and hardware layers of network systems with support for visual and persistent component-based modeling. The dissertation concludes with a discussion of future extension of the SESM/DOC environment and research directions.

2 BACKGROUND AND RELATED WORKS

In Chapter 1, we introduced one of the problems in system engineering, how to efficiently design a large-scale and complex software/hardware co-design network system. In Chapter 2, we go into some details that illustrate the modeling and simulation approaches used in system design.

2.1 System Engineering Overview

With the pervasiveness of computers, the problems that we handle become more and more complicated, and the scope of these problems becomes larger and larger. These problems need to be reviewed from a system point of view. A system is a construct or collection of different elements that together produce results not obtainable by just an individual element. The elements, or parts, can include people, hardware, software, facilities, polices and documents (Blanchard, 2004). These kinds of system problems produce, at minimum, the following challenges (Sage & Armstrong, 2000):

- Many considerations and interrelationships within the system
- Many different and perhaps controversial value judgments
- Knowledge of several different disciplines
- Knowledge at the different levels of principles, practices, and perspectives
- Considerations involving product definition, development, and deployment
- Risks and uncertainties which are difficult to predict
- A fragmented decision making structure

The list of the challenges can be endless. The only way to handle these challenges is through system engineering. System engineering is a field that originated around the time of World War II. Large or highly complex engineering projects, such as the development of a new airliner or warship, are often broken down into stages and managed throughout the entire life of the product or system. System engineering is the intellectual, academic, and professional discipline with the concern that the responsibility to ensure that all requirements for a system are satisfied throughout the life cycle of the system (Wymore, 1993). System engineering is a bridge between the system problems and their solutions provided by technology by performing the following functions (Sage & Armstrong, 2000):

- develop statements of system problems comprehensively, precisely without ambiguities, without eliminating the ideal in favor of the merely practical
- resolve top level problems into simpler problems that can be solved by current technologies
- integrate the solutions to the simpler problems into systems to solve the top level problem

System engineering ensures that a system satisfies all of its requirements. These requirements are in six categories: input/output, technology, performance, cost, tradeoff, and system test. These have been defined in terms of system design (Wymore, 1993). System engineering includes three major concerns: structure, function and purpose. System engineering structure is the management of technology for the formulation,

analysis and interpretation of the impacts of policies based on the need of different stakeholders. The purpose of system engineering is to organize the system engineers to work harmoniously on a large-scale system to make sure that the components of the system cooperate and finish the system tasks. For a large-scale and complex system, system engineers follow some essential steps to handle the complexity:

1) decompose a large issue into smaller, more easily understandable parts;

2) study the individual parts;

3) aggregation of the results to find a solution to the original major issue.

Since system engineering usually handles large-scale and complex systems, understanding the system knowledge is important for the design and analysis of system.

2.1.1 System Design

To design a system is to develop a model on the basis of which a real system can be built, developed, or deployed that will satisfy all its requirements (Wymore, 1993). System design is the process or the art of defining the software and hardware architecture, components, modules, interfaces, and data for a system to satisfy specified requirements. From the system theory point of view, the system design problem can be described as stating the input-output relationships, the design constraints, and the performance and cost figures of merit (Asimow, 1962; Chapman, Bahill, & Wymore, 1992; Skyttner, 2001; Wymore, 1993). System design is important for system engineering which 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 and schedule, performance, training and support, test, manufacturing and disposal (Asimow, 1962).

The task of system design includes the decomposition, statement of the design problem, the architectures, and the functional and the physical representation of the system. These functions can be formalized as detailed functions with both inputs and outputs (Buede, 2000). Table 1 gives the name of functions and their input and output information.

Table 1

Design Process Functions

Design Functions	Inputs	Outputs
Define design problem	Stakeholders' requirements	Originating requirements, operational concept
Develop system functional architecture	Original requirements, operational concept	Functional architecture
Develop system physical architecture	Originating requirements	Physical architecture
Develop interface	Functional architecture	Interface architecture
Develop qualification system	Originating requirements	Qualification system, design documentation

For large-scale and complex systems such as a large-scale networks system, the system design is a very complicated task and it is a NP-complete problem (Chapman, Rozenblit, & Bahill, 2001). The network system is a complicated system due to tremendous factors which must be considered during the network system design. System design is a creative process; that means it is usually applied to a system to be created – one that has not existed before or one that is to replace an existing system. Modeling and simulation methodologies and tools play the highly important role in scalable system

design and analysis, and make the design and analysis procedure better and faster through the above mentioned methods (Zeigler, Praehofer, & Kim, 2000).

2.1.2 Simulation-based System Design

Usually, given the real system (or the imagined system), the system designer will abstract some of the specifications of the system or system components based on their needs to set up specified logical models. The designer can then transform logical models into simulation models and run simulations. During the procedure of creating alternative models and running simulations, designers can gain an understanding of which design solutions best satisfy the requirements. This is important for the designer's decision making. The visual model and the physical model extend the procedure with model visualization and the ability to manage model data in the database.

The design process can be described as a set of iterations of trying out alternative models. Based on the requirements, designers set up a set of initial models and carry out the simulation. After obtaining the simulation results, designers analyze the data and compare the results to the system requirements. Then, a second set of models is made and further simulations are run to get data fromthe new model. The analysis results, again, are compared to the requirements. This kind of model-simulate-analysis procedure will be iterated many times until the analysis results from modeling and simulation match the requirements or the "best" models are found (Wasson, 2006). The whole system design process can be simplified as a closed loop with modeling and simulation as shown in Figure 1.

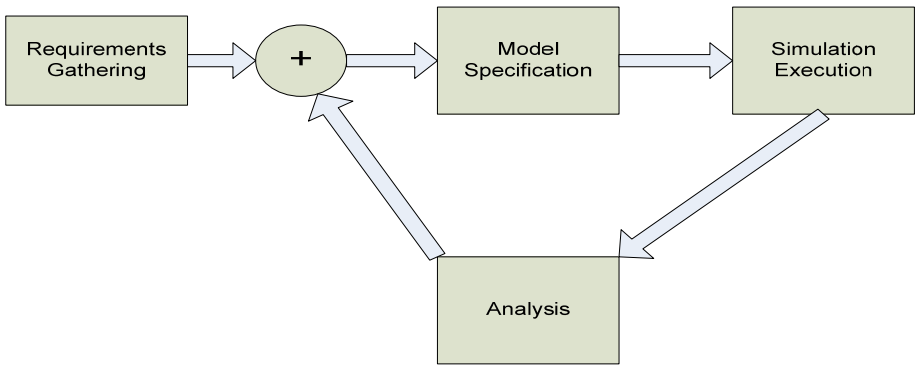


Figure 1. System Design with Modeling and Simulation

A well-defined model should specify both the structure and behavioral properties of a system. Additionally, in order to better assist designers, there are some requirements and "better to be" for modeling and simulation:

- specification models can be distinguished from one another, depend upon the desired resolution and the aspect of the system that is being modeled;
- models can be assembled and grouped with each other into one of the two basic categorized models: basic model unit and composed model;
- logical models can be transformed into simulation models, which can then be simulated in a simulation engine;
- logical models should be stored to help with reuse;
- model data can be transformed into forms that can be simulated;
- visual models, logical models and physical models need to be consistent in the same system;
- models and simulation needs to be verified and validated;

These requirements for modeling and simulation in system design help designers reduce the number of design iterations shown in Figure 1. For example, with the physical model data repository, designers can reuse part of a previous designed model set for a new iteration and avoid the reinvention of the wheel. Furthermore, the verification and validation (V&V) can help designers have the confidence in the accreditation of the modeling and simulation (Hwang & Zeigler, 2006).

A well-defined modeling and simulation methodology and its tools also help with the handling of the design of a large-scale complex system. For example, the decomposition ability of a well-defined modeling and simulation framework can provide varieties of resolutions and aspects of a large-scale and complex system, which is important for designers.

2.2 Modeling and Simulation Concepts

The separation of different levels of system knowledge is essential to modeling and simulation (Zeigler, Praehofer, & Kim, 2000). Depending on different purposes, system knowledge can be grouped into different levels (Klir, 1985), as in Table 2.

Table 2

System Knowledge Hierarchy

Level	Name	Knowledge
0	Source	Variables and how to observe variables
1	Data	Data collected from a source system
2	Generative	Means to generate data
3	Structure	Components and coupling relations in a system

The transitions among different levels can be used to define some fundamental problems in system engineering (Zeigler, Praehofer, & Kim, 2000), such as system analysis and system design.

System analysis: Trying to understand the system behavioral characteristics by generating data under certain instructions. No more detailed knowledge is obtained but something that we may not have been aware of before may come to light. The knowledge transition is from a higher level to a lower level.

System design: Trying to define system components by analysis system requirements. In system design we may have the requirements for the data and need to come up with the design of the system's structural or functional components. The knowledge transition is from a lower level to a higher level.

A specification prescribes, in a complete, precise, verifiable manner, the requirements, design, behavior, or characteristics of a system or system component (SEI, 2000). A system specifications prescribe a system in a complete, precise and verifiable manner. Table 3 shows a level set for specifications based upon timing information.

Table 3

System Specification Hierarchy

Level	Specification Name	Description Contents
0	Observation frame	Observation of variables over a time base
1	I/O behavior	Collection of time-indexed data, consists of input/output pairs
2	I/O function	Initial state, procedure of generating the output with initial state and input
3	State transition	Inputs effects on state, the relation of next state and input and current state, the output

		even generated by a state
4	Structure system	Components and coupling, component and their sub hierarchical structure

Table 3 introduces two more concepts than Table 2, time and state. Time and state are highly related to each other in a system. The system specification hierarchy provides the basis for system morphisms (Zeigler, Praehofer, & Kim, 2000).

2.2.1 System Formalisms

There are many ways to describe a system. A variety of approaches exist for modeling the behavior of dynamic systems. System theory offers discrete-time, continuous, and discrete-event modeling approaches. The traditional differential equation systems, which have continuous states and continuous time, are formulated as Differential Equation System Specifications (DESS). Systems operated on a discrete time base such as automata are formulated as Discrete Time System Specifications (DTSS). If a system operated on a discrete event base, it is formulated as DEVS. DEVS is important to simulate the discrete event system. It also provides a computational basis for implementing behaviors that are expressed in DTSS and DESS. From a system engineering point of view, DEVS is presented in a more general form in system theory. The benefit of DEVS for control and design is clear today with a variety of discrete event dynamic system formalisms such as Petri nets, min-max algebra, and generalized semi-Markov processes (GSMP). The basic motivation that makes DEVS an attractive formalism is that DEVS is intrinsically tuned to the capabilities and limitations of digital computers (Zeigler, Praehofer, & Kim, 2000). There are three kinds of simulation

strategies employed in DEVS: event scheduling, activity scanning, and process interaction. These simulation strategies are also called DEVS "world views" (Zeigler, Praehofer, & Kim, 2000).

2.2.2 Basic Model Types

The most important modeling types in this dissertation are: the logical model, the visual model, the persistent model, and the simulation model. These distinct logical, visual, and persistent modeling concepts are important toward systemically describing structure and behavior of complex systems (Sarjoughian, 2005). The separation of model types also helps with automatic simulation model (or code) generation.

Logical Model – The logical model is the mathematical expression of a real system. It provides the model information with mathematical specifications, for example, DEVS model specifications (Zeigler, Praehofer, & Kim, 2000). Usually, the logical model is the foundation of other basic model types (Banks, Carson, Nelson, & Nicol, 2004; Fishwick, 1995; Fujimoto, 2000; Wymore, 1993).

Visual Model – The visual model is the visual presentation of the logical model and the most human friendly presentation of the logical model. The visual model can be both static (graphic) and dynamic (animated). A static visual model usually presents the structure of the logical model, while a dynamic visual model presents the behavior of the logical model. For the system designer, the visual model is the most convenient way to describe the logical model which they have in their mind. Also, it is the easiest way to review a the logical model coming from different designers.

Persistent Model – The persistent model is the data presentation of the logical model. The persistent model can be reposited in either a database or flat files. The persistent model can be described by data schema. For example, the ER diagram is the description of the persistent model stored in a relational database. Persistent modeling involves the actual design of a database according to the requirements that are established during creation of logical modeling (Stephens & Plew, 2006). The persistent model is stored in the database as tables. By designing different queries for the persistent model in the database, the designer can ask for different aspects of the logical model. For example, a persistent model of an antivirus system can be stored as several tables in a database. By making different queries, the designer can get different information which may not be obtained from the visual models, such as the information of what kind of variables a particular port can receive. With the storage of the persistent model, the designer can reuse the logical model designed previously and make models persistent.

Simulation Model – The simulation model is the code representation of the logical model. The simulation model is aimed to run in a simulator (or simulation environment) to show the data structure and behavior properties of the logical model. The simulation model is important in terms of model validation. The logical model behavior can only be validated by analyzing the simulation results. Also, the simulation model is an essential part of the modeling and simulation process in system design due to its ability to provide simulation data for analysis. Practically, the purpose of creating a logical model is to simulate it and show how the model behaves so that the designer can make decisions about the structure and behavioral specifications and implementations of the real system.

2.2.3 System Morphisms

Modern modeling and simulation (M&S) is based on system theory (Zeigler, Praehofer, & Kim, 2000). The use of system engineering in analysis and design helps the development of modeling and simulation. System theory provides a sound theory basis to support modeling and simulation methodology.

The system morphism is an abstraction of a structure-preserving process between two system structures. Within the concerns of system specification hierarchy, a system morphism is a relation that places elements of system descriptions into correspondence as outlined in Table 3. In fact, morphism is the description of the similarity between pairs of systems at the same system specification level.

Establishing a consistent and correct similarity relationship among systems and models is essential for modeling and simulation. Table 4 shows morphism relations between systems in a system specification hierarchy.

Table 4

System Morphism Precondition in System Specification Hierarchy

Specification level	Specification name	Morphical preconditions for two systems
0	Observation frame	Systems' inputs, outputs and time base can be put into correspondence
1	I/O behavior	Morphic at level 0, time-indexed input/output pairs constituting their I/O behaviors match up in one-one fashion
2	I/O function	Morphic at level 0, the I/O functions associated with corresponding states are the same
3	State transition	Homomorphic
4	Coupled component	Corresponding components are morphic, the coupling among them are equal

Homomorphism is a concept that applies to each of the specification levels shown in Table 4. For example, in Level 3 (State transition) there is a concept called "homomorphic", which is the most important morphism (Zeigler, Praehofer, & Kim, 2000). Theories of homomorphism provide the basis to specify relationships among models and systems which are "similar" to one another. Homomorphism is important to modeling and simulation. It offers a formal basis for showing that a system or model has the functional capability of another under three general settings: homomorphism (a model that is a simplification or elaboration of another), isomorphism (two models are essentially the same models except for their notation and ports), and copies (two models are the same, including their interfaces). To illustrate how two systems are homomorphic, we need the help from the following figure (Zeigler, Praehofer, & Kim, 2000).

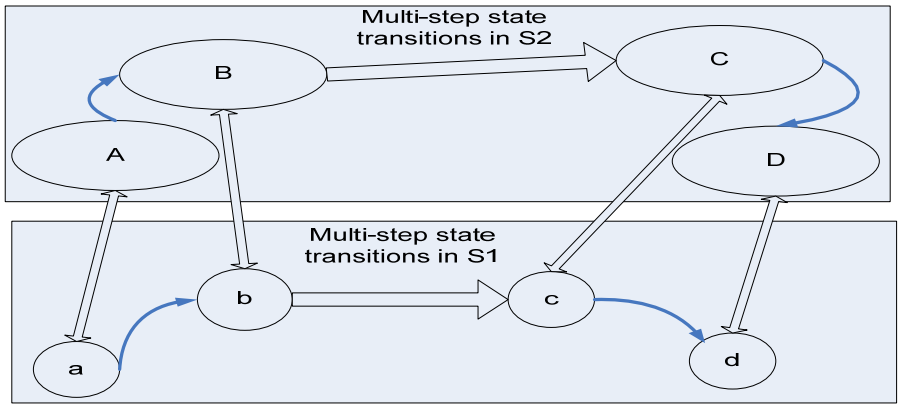


Figure 2. State Transitions in Homomorphic Systems

In Figure 2, S1 and S2 are two systems with multiple states specified at Level 3. When S1 goes through a state sequence *a-b-c-d*, then S2 will go through a corresponding state sequence *A-B-C-D*. The states in S1 and S2 are not necessary identical. If whenever S1 specifies a transition, for example, from state *b* to state *c*, S2 will make the transition

involving corresponding states *B* and *C*. Then, there is a homomorphism between S1 and S2. That means any state trajectory in system S2 will be properly reproduced in S1.

2.2.4 Verification and Validation

Assuring the use of a modeling and simulation methodology requires the measurement and assessment of a variety of quality characteristics, such as accuracy, execution efficiency, maintainability, portability, reusability, and usability (human-computer interface)(Schulz, Rozenblit, & Buchenrieder, 2002). Here the accuracy, which needs the verification, validation and accreditation of modeling and simulation, is the important part of the model development process if models are to be accepted and used to support decision making for system design. There are many definitions for verification and validation (V&V) and accreditation (Sargent, 2000; Schilesinger, 1979). In this dissertation, their definitions for modeling and simulation are (Zeigler & Sarjoughian, 2002):

Verification: The process of determining that a model implementation and its associated data accurately represent the developer's conceptual description and specification.

Validation: The process of determining the degree to which a model and its associated data are an accurate representation of the real-world from the perspective of the intended uses of the model.

Accreditation: The certification that a model, simulation, or federation (federation: sets of federates; federate: simulations, supporting utilities, or interfaces to

live systems (Institute of Electrical and Electronics Engineers, 2000)) of models and simulations and its associated data are acceptable for use for a specific purpose.

To summarize, model verification is concerned with whether the implementation of the model is right. Model validation is concerned whether the model is the right model. And accreditation is concerned with whether the modeling and simulation is acceptable for use. To know the principles for verification, validation and accreditation (VV&A) of modeling and simulation (M&S), it is important to understand the foundations of VV&A. Osman Balci and the Department of Defense provide some guidelines for the details of the verification, validation and accreditation of modeling and simulation (Balci, 1997). For example, a simulation model is built with respect to the M&S objectives. Errors should be detected as early as possible in the M&S life cycle. Successfully testing each sub-model (module) does not necessarily imply overall model credibility.

2.3 Software Engineering

Software engineering plays an important role in system modeling and simulation. More and more applications use software tools to present the logical model and use software simulators to run simulations.

Nowadays, with the scale and complexity growth in system engineering, more and more computer technology is involved in system design. This makes software engineering play an important role in system engineering. Software engineering, as defined by IEEE, is the application of a systematic, disciplined, quantifiable approach to the development, operation, and maintenance of software; that is, the application of

engineering to software (IEEE, 1993). There are two kinds of software engineering applications in system engineering. One is that more and more embedded software are built in system hardware components; the other is that more and more software technology is used in the system level design. Software engineering, from one point of view, is a consequence of system engineering (Pressman, 2005).

These kinds of software applications distinguish the software engineering in system design from traditional "pure" software engineering in the sense that the software works together with the hardware, the communication among the software components are realized by the hardware components in a system so that the design of the software architecture depends on the constraints from the hardware.

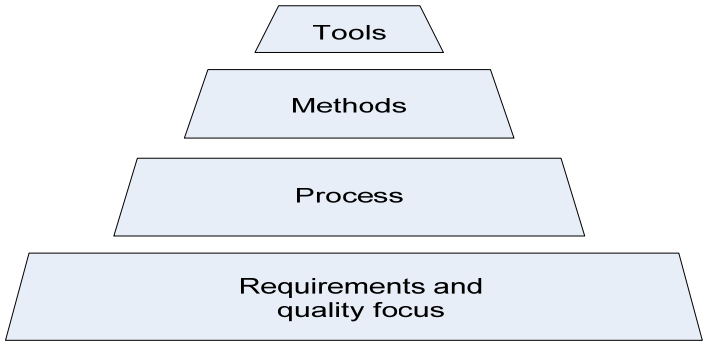


Figure 3. Software Engineering Layers

The whole software engineering is a layered technology (Pressman, 2005). Figure 3 shows the layers in software engineering. The foundation for software engineering is the system requirements and a set of quality concerns. These provide the requirements and constraints to software engineering. The process layer defines a procedure for tasks, activities, and milestones which are required in the software development life cycle. Methods in software engineering provide the details of building a software product. The

method layer includes all of the major tasks in software development such as requirements analysis, design modeling, program construction, and testing. The tools layer provides support for the process and methods. Tools can be integrated so that the information can be shared within the software system and the support of software development, computer-aided software engineering can be created (Pressman, 2005).

Modern complex systems including software, hardware, databases, and documentation, can be defined as a computer-based systems, which are a set of elements organized to accomplish some predefined goal by processing information (Pressman, 2005). With the involvement of software engineering, the system designer needs to handle the issues related to software engineering such as software process models, software analysis and design, and software testing.

Software Process Models: All software development tasks and activities follow a software development process models. A process model provides the rational and timely development for software products. With the development of software engineering, there have been many process models applied to for software development. These include the waterfall model, the incremental model, and the evolutionary models.

The waterfall model is the most traditional software development process model. It follows the sequence: requirements analysis-design-coding-testing. It is good for the situations where requirements are fixed and the work needs to be done in a linear manner. The incremental process model also follows the linear process, but with an iterative flavor. In each linear sequence, the incremental model provides deliverable “increments” of the software product (McDermid & Rook, 1993). Incremental development is useful

when software engineers are not available for a complete version of the software product by the business deadline. The evolutionary process model is iterative. It enables software engineers to develop increasingly more complete versions of software products. The prototyping model and the spiral model are two typical evolutionary models. The intent of the evolutionary model is to develop software with flexibility, extensibility and high speed. It is important for software engineers to maintain a balance between customer satisfaction and development speed.

Software Design: Software design is the essential part of the software development process. A good design not only makes the development process smooth, but also provides positive effects to software product quality. Based on the requirements analysis, software design creates a set of design models to represent software components and the relationship among the components. These design models provide detailed information about basic issues in developing software products such as data structures, architectures, and interfaces.

There are three major steps in software design: software system architecture design, system interface design, and components design. Software architecture is the overall structure of the software product and the way that the components of the software integrate together (Shaw & Garlan, 1996). Software architecture is important in the sense that it determines how the software system can be created and how the system works. Software interface defines how the software system interacts with other systems. There are three kinds of interface: software system to software system, software system to hardware system, and software system to people. After the architecture design and

interface design, the last design step is the detailed components design which will give the detailed instruction for programming.

Software Testing: Software testing is used to uncover the errors made during the design and construction process. It is the major element of the concept of software verification and validation (V&V). Software verification is the activity that ensures that the software product implements a particular function correctly. Validation ensures that the software product is traceable to customer requirements (Pressman, 2005). Besides software testing, V&V also includes software quality assurance activities such as formal technical reviews, quality and configuration audits, and performance monitoring. Software testing is an essential part of V&V.

During software development, software testing strategies and testing techniques are helpful for test planning and implementation. Software testing strategy integrates software test cases into a well-defined series of testing steps. The examples of typical software strategy are unit testing, integration testing, and top-down integration. Software testing techniques are the detailed methods to design test cases during software testing. A good testing technique should provide test case operability, observability, controllability, and simplicity. Basic software testing techniques include black-box and white-box testing, basic path testing, and control structure testing. (Pressman, 2005)

2.3.1 Use of Software Engineering in Simulation Tools

As a way of implementation, software engineering plays an essential role in modeling and simulation. The relationship between the concepts of software and the

model is very tight and, as a result, sometimes it is hard to separate them. A software module may be looked at as a model because its execution presents a set of particular behavioral properties. Also, in the object-oriented programming paradigm, a model can be implemented by one or more classes. This kind of closed relationship makes a good software design helpful to modeling and simulation. The modeling and simulation provides requirements and constraints for software development. Model-View-Control (MVC) and testing are two elements in software engineering with regard to modeling and simulation.

Model-View-Control (MVC): MVC is an architectural design patterns. Design patterns provide standard solutions to common problems in software design. These solutions can be reused in same design scenarios. MVC design pattern breaks the system into three parts: the model, the view and the controller. Originally, MVC was developed to map the traditional input, processing, and output roles into the GUI realm as in Figure 4.

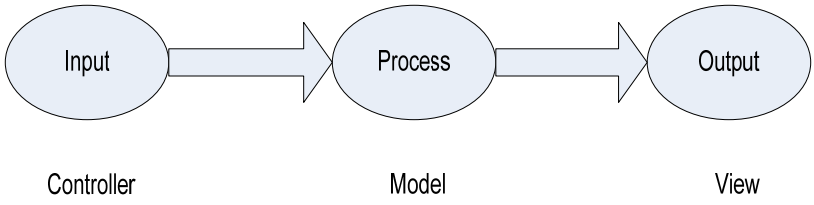


Figure 4. Motivation of MVC

MVC has been widely used in software system deign to obtain the separation of different functional software modules (Eker et al., 2003; Ferayorni & Sarjoughian, 2007; Gamma, Helm, Johnson, & Vissides, 1995; Nutaro & Hammonds, 2004; Sarjoughian &

Singh, 2004). The model in MVC manages model data elements, responds to queries coming from a controller about the state, and responds to controller instructions to change the state. The view receives the model data and presents data to the user through a combination of graphics and text. The view is the only place the user can get information out of the process. The controller is the unit to interpret mouse and keyboard (or other input devices) inputs from the user and transforms them into commands. The controller sends these commands to the model and the view so that appropriate change will happen in the model side and the view side. As the system becomes complicated, the interaction inside MVC becomes important. Depending on system requirements, there are different kinds of MVCs that can be set up. Figure 5 shows a MVC whose Controller reads and writes to the Model, but only writes to View.

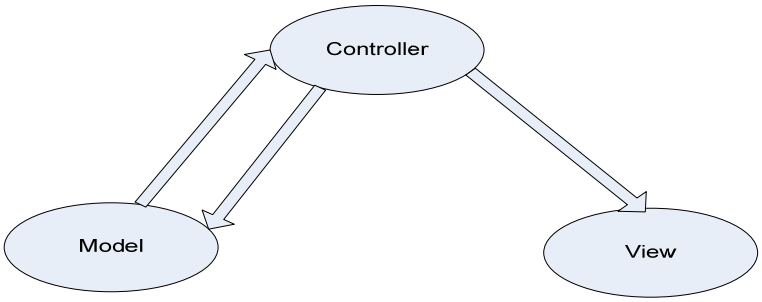


Figure 5. MVC Example

MVC provides some insight to the visual modeling approach provided in this dissertation. A point to be emphasized is that for the SESM/DOC environment both the control and view are in the same place.

2.4 Model-Driven Engineering

There is always a gap between the field of system design and the field of modeling and simulation. On one hand, system designers have the domain knowledge of the system but they may not have the training for writing the simulation model code to run the simulation. On the other hand, modeling and simulation people have the skills to write the simulation model code, but they don't know how to set up the logical model and how to make verification and validation according to particular domain knowledge. The consequence is that either the system designer spends too much time learning to write the simulation code (which may not properly reflect the logical model), or the system designer spends too much time communicating with the simulation people to make sure the simulation people understand the rationale inside the model. The result of this kind of communication always leads to unsatisfactory simulation code due to the lack of domain knowledge background on the part of the simulation people. In reality, even within the people who have the domain knowledge, their levels of capability to handle the problem related to domain knowledge are different. It is commonly accepted within industry, such as the network industry, that fewer than 10% of engineers working in the field have sufficient knowledge and experience to tackle the complexity in the design phases; that is to say, only this group of people can process the knowledge and overview of the elusive system architecture that allows them to identify the details in network nodes, network services, protocols, and messages that will be affected by changing network functionalities. The other 90% of engineers are capable of performing the execution

phase which means they can only operate the system (Muth, 2005). This generalization serves as one of the motivations behind the attempts to automate the generation of the code for proprietary programming language, which later gradually becomes a reality for standardized language.

Another major challenge regarding system design in modeling and simulation is how to transform models among different platforms. In recent years, some popular middleware platforms such as J2EE (SUN, 2005), .NET(Microsoft, 2006) and CORBA(Object Management Group, 2005) have grown rapidly. These platforms contain thousands of classes and methods with many intricate dependencies and subtle side effects. Designers have to expend extra effort manually porting application code to different platforms. This process is time consuming and error prone.

Model-driven engineering (MDE) is the bridge between the domain knowledge and the modeling and simulation. Several MDE methodologies are provided to try to solve the above problems by integrating the process of design and lower level implementation. Computer-Aided Software Engineering (CASE), Model-Integrated Computing (MIC), and Model-Driven Architecture (MDA) are the three major ones among the MDE methodologies.

Computer-Aided Software Engineering (CASE) began in the 1980s. It provides general purpose graphical programming representations such as state machines, structure diagrams, and dataflow diagrams to the designer in order to describe their thoughts for the system (Schmidt, 2006). This helps designers to avoid detailed language implementation. However, CASE has some fatal problems. One is that there is still a gap

between the designer and the people who do the detail implementation. The programmers have to read the graphical representations to understand the design before they start to do the modeling and simulation. It is very easy for a misunderstanding to occur in this process. The other problem is the implementation code is not generated automatically, which means people still need to manually code. This is tedious and time consuming. Those problems make CASE have relatively little impact on commercial system development. EDEN (Erdogan, McFarr, & Maglidt, 1989) and AVAT (Dai & Scott, 1995) are examples of CASE. Therefore, the current most popular MDE methodologies are MIC and MDA.

2.4.1 Model-Integrated Computing (MIC)

Model-Integrated Computing (MIC) has been developed over a decade at the Institute for Software Integrated System (ISIS), Vanderbilt University. This approach extends the usage scope of models so that they can form the "backbone" of the model-and-simulation integration process. The key elements in MIC are (Schmidt, 2006):

Domain-Specific modeling language (DSML) – DSML is a kind of language whose type systems formalize the structure, behavior, and constraints of particular application domains, such as the computer network systems, the supply chain networks, and online financial services. It uses meta-models which is the basic unit model defining the relationships among concepts within a domain and precisely specifies the semantics and constraints associated with these domain concepts. Using DSML, designers can express design intent declaratively rather than imperatively. For example, when a

designer wants to design an antivirus system, what he needs to do is just declare what kind of processor (single thread or multiple threads) should be in the system; he has no need to code the command line by line to implement it.

Transformation engine and generators – Transformation engine and generators can analyze certain aspects of models and then synthesize other type of artifacts such as the simulation model source code, and XML description. The source code generated can be run in a simulator. The transformation engine and generator can also help designers check to determine if the models specified in DSML are correct according to the domain constraints by running the simulation code. The life cycle of MIC (Gokhale, Batarajan, Schmidt, & Wang, 2002) is illustrated in Figure 6.

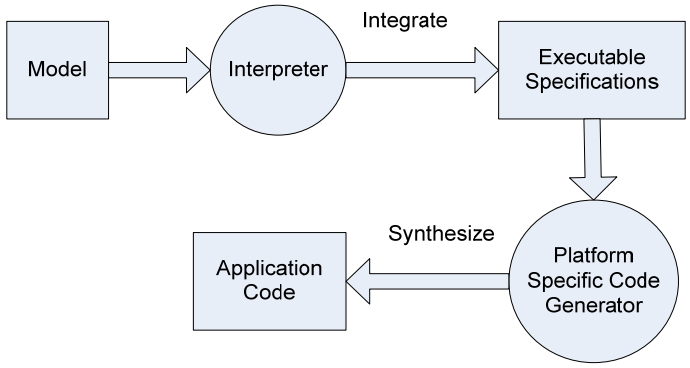


Figure 6. Model-Integrated Computing Life Cycle

Model-Integrated Computing helps the system designer avoid the trouble of the implementation of their models. A well-defined DSML can automatically generate the simulation code. With MIC, system designers can shift their focus of modeling and simulation from implementation technology domain towards the concepts and semantics in the problem domain. The debugging and the model checking can be done in the

modeling level but not the detailed code level. Even for the people who are familiar with implementation of the simulation model, the MDE reduces costs and shortens the time to market. Automatic generation of code is always faster than manual generation. Examples of MIC are CoSMIC and ECSL (Krishnakumar, Gokhale, & Karsai, 2006).

However, there are still some drawbacks to MIC in practice. First, the application of a particular DSML is very limited because it is only for one domain. Second, the designer has to learn how to use the DSML to describe logical models. DSML is much easier than a general purpose language like C++. However, if designers need to do design for several domains then they have to be familiar with a different DSML and the learning curve becomes bigger.

2.4.2 Model-Driven Architecture (MDA)

Model-Driven Architecture (MDA) was defined and trademarked by the Object Management Group (OMG) in 2002. Unlike MIC, MDA presents systems using OMG's general-purpose Unified Modeling Language (UML) (and its according profile, which is the extensions of UML) and transforms these models into artifacts which can run on different platforms such as EJB, .NET, and the CORBA Component Model (CCM).

Using MDA, the system designers can use the UML present logical model. This makes the logical models have unified syntax and can be shared between designers easily. A UML presented logical model is known as Platform Independent Model (PIM). UML is a malleable language and provides a build-in extension mechanism. Adding with build-ins, UML can support middleware-specific modeling. This extension of UML is

called UML profiles (Frankel, 2003). UML profiles can help transform a Platform Independent Model (PIM) to a Platform Specific Model (PSM). The further step is to transform PSM to a source code which can run in the particular platform. The procedure in MDA is shown in Figure 7.

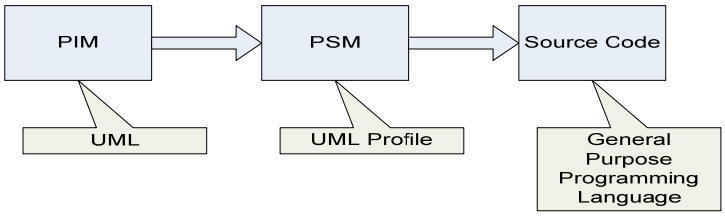


Figure 7. Model-Driven Architecture Procedure

In MDA, designers use their expertise to develop PIM. They do not need to worry about the platform issues and coding details – this highly improves the productivity. The UML in MDA helps to standardize the logical model. The same PIM can be automatically transformed into a variable PSM for different purposes. This makes the design more portable. The MDA framework raises the level of abstraction of the system design. IBM Rational Rose XDE is a MDA example which combines a modeling environment with a code-oriented tool set to create solutions in a variety of architectural styles (Brown, 2004). Another MDA example is MODEST (Model-Driven Enterprise System Transformer), which was developed by Chronos Software, Inc (Rutherford & Wolf, 2003).

MDA makes a big step for the integration of design and implementation. However, there are still major drawbacks in MDA. First, as the language to define a PIM, UML has some limitations. UML is designed along with the object-oriented concepts. So

to define a non-object-oriented model, designers need to create a new meta-model, which is error prone and time consuming. UML shows its strength as a unified language but as the side effect it looses the particularity in a particular domain. Using UML to present a set of domain knowledge is not easy. In order to generate the executable code, MDA needs two steps of transformation: transformation from PIM to PSM and transformation from PSM to code. This means that MDA can only provide a code template which needs extra work (manually) to add some behavior functions to run. Used in the modeling and simulation field, MDA cannot realize the real model-and-simulate paradigm.

2.4.3 Model Design Methods and Tools

The model design plays an important role in model driven engineering. The model design for a system is not trivial. The model designer needs the knowledge of system engineering, software engineering, and the system domain knowledge, etc. There are methodologies and tools to help people to specify and design the model. In this section we will introduce some of them.

Entity Relationship (ER) Modeling: Entity Relationship Modeling is a type of conceptual data model which is used in relational database design (Chen, 1976). The graphic view of ER model is ER diagram, which represents the conceptual database as viewed by the end user. The ER model has three main components: entities, attributes, and relationships. An entity refers to a table or an object in the database. Attributes are particular properties that describe the entity. Each entity has at lease one attribute. A relationship refers to an association between entities. ER modeling translates different

views of data among database designers, programmers, and database users. The ER diagram defines data processing and constraint requirements in order to help meet the different views and implement the database. Through the ER diagram, the data model entities, the attributes these entities contain, and the relationships among these entities are clearly presented.

System Entity Structure (SES): System Entity Structure is a structural knowledge representation that systematically organizes a family of possible structures of a system (Zeigler, Praehofer, & Kim, 2000). This kind of family includes system entities as well as the decomposition and coupling relationships. In SES, an entity is a model of a real world object. The decomposition is the process of how an entity can be broken into sub-entities. These sub-entities may be decomposed further. The coupling relationship specifies how sub-entities in an entity can relate together and reconstitute the entity. SES is based on system theory and gives the hierarchical decomposition structure of a system. SES aids in the design and analysis of a complex system by breaking it down into finite small and easy subsystems.

Extensible Markup Language (XML): Another data modeling language is XML. XML is a general-purpose markup language. Its primary purpose is to facilitate the sharing of data across different information systems, particularly via the Internet. XML allows a user to define a model in a markup language and share the model information in different platforms.

XML is a simplified subset of the Standard Generalized Markup Language (SGML) and is designed to be relatively human-legible. By adding semantic constraints,

application languages can be implemented in XML. These include XHTML, RSS, Scalable Vector Graphics, and thousands of others. Moreover, XML is sometimes used as the specification language for such application languages. XML is recommended by the World Wide Web Consortium (W3C). It is a fee-free open standard. The W3C recommendation specifies both the lexical grammar and the requirements for parsing. (World Wide Web Consortium, 1998)

Unified Modeling Language (UML): The Unified Modeling Language is a standardized specification language for object modeling in the field of software engineering (World Wide Web Consortium, 1998). UML is officially defined at the Object Management Group (OMG) by the UML metamodel, a Meta-Object Facility (MOF) metamodel. It is a general-purpose modeling language that includes a graphical notation used to create an abstract model of a system, referred to as a UML model. UML was designed to specify, visualize, construct, and document software-intensive systems. UML has been a catalyst for the evolution of model-driven technologies, which include Model Driven Development (MDD), Model Driven Engineering (MDE), and Model Driven Architecture (MDA). By establishing an industry consensus on a graphic notation to represent common concepts like classes, components, generalization, aggregation, and behaviors, UML has allowed software developers to concentrate more on design and architecture.

UML is not restricted to modeling software. It is also used for data modeling, business process modeling, systems engineering modeling, and representing organizational structures. UML is extensible, offering both profiles and stereotype

mechanisms for customization. The semantics of extension by profiles has been improved with the UML 2.0 major revision. The current version of UML (early 2007) is Version 2.1.1.

Systems Modeling Language (SysML): Systems Modeling Language is a domain specific modeling language for system engineering. It supports the specification, analysis, design, verification and validation of systems. SysML has improvements over UML such as: having more flexible and expressive symatics, easier to being learned and applied, and supporting common kinds of table allocations. SysmML reduces UML's size and software bias while extending its semantics to model requirements and parametric constraints. (Hause, Thom, & Moore, 2005)

Scalable Entity Structure Modeler (SESM): Scalable Entity Structure Modeler (Fu, 2002) is a framework aimed at hierarchical component-based modeling. Its specification capabilities are derived from ER, System Entity Structure (SES), and Object-Oriented (OO) modeling approaches. It introduces visual modeling and the transformation of logical models into simulation models. In its realization, SESM is a modeling engine for developing specifications that have formal logical syntax and semantics as well as visual and persistent representations. The simulation model can be partially generated based on the models which are stored in the database.

Many modeling and simulation software products are used in academia and industry. Some popular generic system modeling and simulation tools are MATLAB (Higham & Higham, 2000), Simulink (Karris, 2006), DEVSJAVA (Arizona Center for Integrative Modeling and Simulation, 2007) and PowerDEVS (Kofman, Lapadula, &

Pagliero, 2003). The work in this dissertation provides co-design modeling methods to support distributed network modeling and focus more on network modeling and simulation. There are a variety of simulation environments that support the modeling of computer networks such as NS-2 (Information Sciences Institute, 2004), GloMoSim (Global Mobile Information Systems Simulation Library, 2005), OPNET (OPNET Technologies, 2004), QualNet (Jaikaeo & Shen, 2005; OPNET Technologies, 2004), TOSSIM (Levis, Lee, Welsh, & Culler, 2003), etc.

NS-2: NS-2 is a discrete event simulator for networking research. It provides support for simulation of Transmission Control Protocol (TCP), routing, and multicast protocols over wired and wireless networks. (Information Sciences Institute, 2004)

In the application layer, NS-2 provides two basic types of applications: traffic generators and simulated applications. There are currently two "simulate application" classes derived from NS-2 Application class: Application/ File Transfer Protocol (FTP) and Application/Telnet. These classes work by advancing the count of packets available to be sent by a TCP transport agent. The actual transmission of available packets is still controlled by TCP's flow and congestion control algorithm. In NS-2, all of the applications are limited to implementations of low level computer networks with the TCP/UDP constrains. NS-2 supports simulation applications for detailed computer networks in the lower level.

In the transport layer, with the support of transport layer agents, NS-2 provides a strong support for the transport protocol simulation. The network level packet header field helps the routing in the NS-2 network layer.

The NS-2 link layer can potentially have many functionalities, such as queuing and link-level retransmission. The need of to have a wide variety of link-level schemes leads to the division of functionality into two components: Queue and LL (link-layer). The Queue object, simulating the interface queue, belongs to a Queue class in NS-2. The LL object implements a particular data link protocol, such as Automatic Repeat Request (ARQ). By combining both the sending and receiving functionalities into one module, the LL object can also support other mechanisms such as piggybacking.

At the bottom of the NS-2 protocol stack, the physical layer is composed of two simulation objects: the Channel and Classifier/Mac. The Channel object simulates the shared medium and supports the medium access mechanisms of the MAC objects on the sending side of the transmission. On the receiving side, the Classifier/Mac is responsible for delivering and optionally replicating packets to the receiving MAC objects.(Chung & Claypool, 2005; Fall & Kannan, 2005).

NS-2 has strong support for the layers under the application layer. However, in the application layer, NS-2 only provides limited facilities for the user to define customized services. In NS-2, the node module is the main part that supports the applications. A node is composed of three parts: address classifier, Port classifier and agents. The address classifier is used to support unicast (although NS-2 also supports multicast, by default, the node is unicast) packet forwarding. The address classifier contains a slot table for forwarding packets to foreign nodes. All packets not destined for this node (and hence forwarded to the port classifier) are sent to the default target, which points to an agent. In NS-2, an agent supports packet generation and reception.

This kind node structure does not provide the management of the work processed in the node so it is hard for the modeler to model and simulate what is going on inside the node when the system is running. It is also hard to present the dynamic behavior of the node unless the extra code is added by the modeler which means the modeling of software is ad hoc and not supported with well-defined specification. Furthermore, there is a strong dependency among some of the NS modules. As a result, it can be challenging to model new protocols or to make changes to existing protocol models. Given its complexity and low-level detailed models, it is necessary to have the knowledge of NS-2 at the software implementation and design level for serious simulation. NS-2 supports the fine grain modeling of protocols rather than the quantum level modeling (Information Sciences Institute, 2004). NS-2 is not intended for disciplined integration of hardware and software simulation modeling. It supports simulating software communication protocols for network devices instead of simulating a set of software applications distributed across processors and network devices.

From a usability aspect, NS-2, which is a Unix-based environment, does not offer a user friendly simulation environment. All of the simulation results are stored in data files (simulation logs). The stepping and control is hard to implement. NS-2 is based on C, which does not provide a purely object-oriented way to set up a model hierarchy. Consequently, the use of NS-2 can require additional time and effort for developing models that are not already available.

GloMoSim: GloMoSim is a library-based sequential and parallel simulator. It is designed as a set of library modules, each of which simulates a specific communication

protocol in the protocol stack. GloMoSim supports its application layer service for wireless network systems. Users can get the low level statistics In the GloMoSim application layer such as the total number of packets sent and the total number of packets dropped. GloMoSim supports wireless FTP and telnet application. The statistics that can be obtained are the start/end time, bytes sent/received and throughput. For the transport layer in GloMoSim, there are various protocols which can be used individually or concurrently. Protocols such as IP with Ad hoc On Demand Distance Vector (AODV), Bellman-Ford, Dynamic Source Routing (DSR), and Fisheye, are supported in the GloMoSim network layer, and Carrier Sense Multiple Access (CSMA), IEEE 802.11 and Multiple Access with Collision Avoidance (MACA) are supported in the link layer. In the physical layer, GloMoSim's models are implemented based on the DSSS PHY reference configuration in the IEEE 802.11 standard (Gerla, Zhang, Tang, & Wang, 1999; Global Mobile Information Systems Simulation Library, 2005; Pei, 1997).

The library in GloMoSim is written in PARSEC, a C-based parallel simulation language. Users have to hard code their own protocols or models if they are not found in the library. Only limited network service models are provided, especially in the application layer.

OPNET: OPNET is a commercial network simulator which was first introduced in 1986. It provides a comprehensive development environment supporting the modeling of communication networks and distributed systems. OPNET has a very user friendly GUI to help the user to build its models (OPNET Technologies, 2004).

In the application layer, the Application Characterization Environment (ACE) in OPNET directly addresses the end-to-end application performance analysis issues. This ACE environment focuses on the application performance monitor instead of providing a flexible mechanism for users to model different user-defined applications in the lower levels. Another package in OPNET, the ACE Decode Module (ADM) provides some pre-defined application model and protocols but to modify and customize them in lower levels is a challenge. OPNET also supports the transport layer and can be used to study the impact of TCP and UDP. The analysis data in the transport layer includes data volume sent and received, connection establish/abort counts, and UDP end-to-end latency (Highland System Inc., 2005). OPNET shows its strength in the network layer. Many detailed studies can be made in this layer with OPNET such as different routing protocols. In the link layer, OPNET can be used for both wired networks and wireless networks (Chan, 2005; Zhong, Rabaey, Guo, & Shah, 2001). In the physical layer, OPNET is used to analyze the throughput and received power (Highland System Inc., 2005). The downside is that OPNET has limited scalability. Currently, it only can perform well with no more than hundreds of nodes in the network.

QualNET: QualNet is a high speed network modeling tool used to simulate a wide range of computer networks. It is a commercial derivative of GloMoSim. Its simulation kernel runs a large library of detailed protocol models. In the application layer, QualNet generates traffic based on network protocols such as ftp, and telnet. Users can choose the application layer protocols from the GUI which is connected to the model library. The transport layer in QualNet is in charge of TCP and UDP protocols. QualNet currently

only provides routing protocols in its network layer. The link layer manages the packets store and forward with multiple access control protocols for IEEE 802.11, and 802.3. The physical layer provides a noise model and parameters specific to 802.11b, it also has a omnidirectional antenna model for wireless network (Jaikaeo & Shen, 2005). QualNet shows its strength in large-scale network simulation. However, as was the case in GloMoSim, models which can not be found in the library are hard to add for the simulation.

TOSSIM: TOSSIM is a simulator for embedded systems in sensor networks. Its primary goal is to provide a high fidelity simulation of TinyOS applications. For this reason, TOSSIM focuses on simulating the open source TinyOS and its execution. So the applications that run in TOSSIM are the applications that belong to TinyOS. Also, TOSSIM simulates the network at the bit level. Currently, TOSSIM simulates the 40Kbit RFM mica networking stack, including the MAC, encoding, timing, and synchronous acknowledgements (Levis & Lee, 2003; Levis, Lee, Welsh, & Culler, 2003).

In the real world, numerous systems can be studied as network systems, such as computer networks, supply chain networks, work-follow management, and transportation systems. These are all constructed from two building blocks: nodes and links. The node is a processing/computing unit, and the link is the transportation media. The above simulation environments show their strength for modeling and simulating the link— the transportation media part of the system. However, they do not provide enough facilities for modeling and simulating the nodes— the processing/computing unit. There are two reasons for this. First, all of these simulation environments are not intended for

disciplined integration of hardware and software simulation modeling. They do not separate the implementation of hardware and software. The detailed study of the services in the nodes requires the separation of the models for hardware (resources) and software (services). The second reason is that all of the simulation environments are designed for the study of the computer network protocols. The nodes (or application layer) in these protocols only provide the traffic generation based on basic network protocols such as FTP, and telnet. This limits the usage of these simulation environments only for computer network transportation protocols.

Most of the simulation environments above do not provide a purely inheritance hierarchy relationship for the models. In the above simulation environments, only OPNET provides a formal object-oriented view for models. Some of the simulation environments provide users friendly GUIs such as GloMoSim, OPNET, QualNet, others, such as NS-2, do not. Some of them are good for large-scale simulations, such as QualNet, while some are not, such as OPNET.

DEVS/DOC: The DEVS/DOC approach extends the generic DEVS modeling concepts and models to support co-design specification of network systems. This co-design approach enables modelers, for example, to model a computer network in terms of separate sets of hardware and software components and software to hardware mappings. With this approach, the hardware and software layers can be independently specified and the software to hardware mapping can be used to configure alternative system designs. The flexibility is important for evaluating alternative hardware topologies (e.g., computing resources offered by individual nodes and their combination) given software

functionality and quality attributes (e.g., desirable quality of service afforded by individual software components and their combination) (Hild, Sarjoughian, & Zeigler, 2002).

2.5 Summary

This chapter describes the background and related work for modeling and simulation in the context of system analysis and design. Related concepts in system engineering, system theory, and modeling simulation are reviewed. A survey of the related modeling and simulation frameworks and approaches are given in this chapter to illustrate their strengths and limitations. Compared to the work in this dissertation, these modeling approaches in the survey do not have clear boundaries to systematically define the software and hardware in a network system from the visual and persistent modeling point of view. They do not provide the descriptions of the relationship between the software and hardware model visually. In a word, they fall short of specifying the separation and synthesis of software and hardware components in a co-design network system through visual and persistent modeling.

3 MODELING AND SIMULATION APPROACHES AND TOOLS

In the previous chapters, we briefly introduced SESM, DEVS, and DEVS/DOC. These are the basic elements for the co-design modeling approach developed in this dissertation. Each will be introduced in detail as appropriate.

3.1 Scalable Entity Structure Modeler Concepts and Approach

Scalable Entity Structure Modeler is a modeling methodology for component-based modeling of large-scale and complex systems (Fu, 2002; Sarjoughian, 2001). SESM provides modeling of a system using three complementary model types: Template Model (TM), Instance Template Model (ITM), and Instance Model (IM). A Template Model is defined as either a primitive or a composite component with input and output ports and port values. A primitive template model specification contains state variables and a name. The primitive model is the basic model unit in SESM and cannot be decomposed. A composite model has one or more primitive models or other composite models. The relationship between two connected model (primitive or composite model) ports is called a link (Sarjoughian, Fu, Bendre, & Flasher, 2007). A composite template model specification has links, a name, and it can be defined to have a hierarchy of length of two. The composite model can be decomposed into other composite models or primitive models. This primitive-composite modeling structure allows the system designer to decompose the large-scale complex system and deploy the component models.

The difference between an instance template model and a template model is that an instance template model can have a finite hierarchy with a length greater than two. The instance template models introducing multiple-levels of hierarchy using

decomposition and specification. An instance model is an instantiation of an instance template model where the multiplicity of instances of a model is specified. Usually, a designer creates the template models, instance template models, and instance models in a sequential manner. In the instance model generation stage, the decision of which specified model component to use is made.

The primitive-composite model structure provides the system designer the facility to decompose a large-scale complex system into a finite number of simple systems. The relationship between the three model types gives the system designer the ability to specify different resolutions of the system model. This decomposition helps the system designer create alternative models according to its desired resolution, which are important in the modeling of large heterogeneous systems.

SESM aims to help designers with system design by creating and verifying models for scalable systems such as a network system. SESM captures three sets of system model properties: structure, structural complexity and behavior. Model structure includes the model's name, input and output ports, the coupling relationship between multiple models, and the composition relationship between multiple models. Structural complexity captures the model's structure scale, such as the number of parts. Complexity is important for large-scale systems and hierarchical system models (Bendre & Sarjoughian, 2005; Mohan, 2003; Sarjoughian, 2005). Model behavior includes model input and output value types, and state variables (Bendre, 2004; Bendre & Sarjoughian, 2005).

The goal of the SESM model engine is to handle the modeling of a family of modular, hierarchical models at different levels of abstraction. The support from a database is important for this kind of large-scale modeling in terms of persistence, the persistent model data management, and model transformation. SESM saves the logical models as persistent models using the schemas shown in Figure 8 (Bendre, 2004; Fu, 2002; Mohan, 2003; Sarjoughian, 2005).

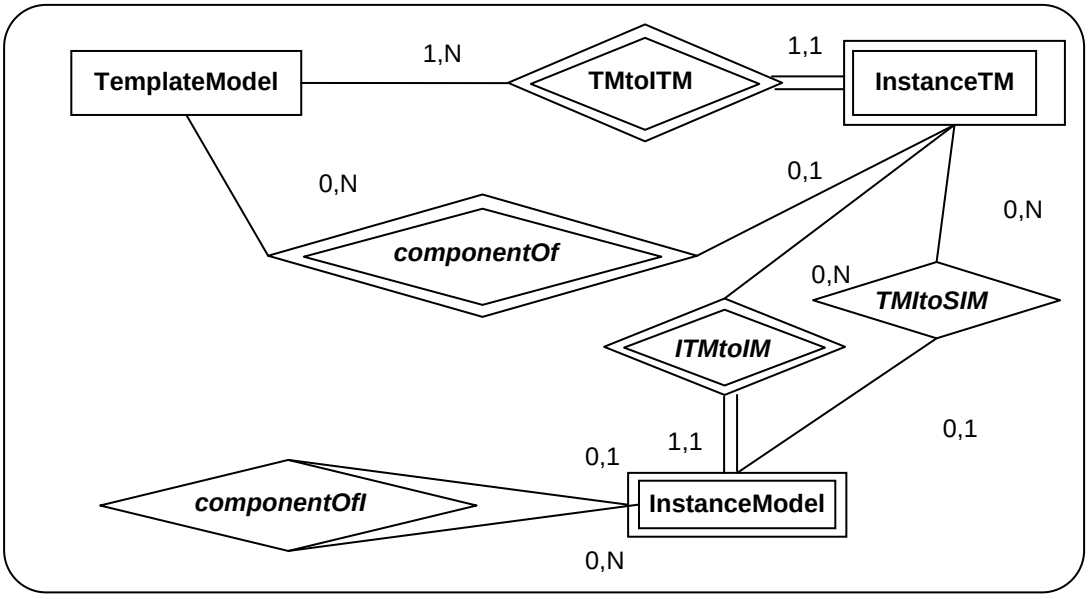


Figure 8. Basic SESM ER Diagram

3.1.1 Framework and Related Modeling and Simulation Architecture

SESM, as a modeling framework, has the following architecture shown in Figure 9. The SESM client includes the user interface through which designers can design and view models. The SESM server stores the models into a database. Clients can read the model data from the database and its "write" requests can be passed through the server to

the database. The server can both “write” and “read” to the database. Figure 9 shows the data flow in the SESM architecture.

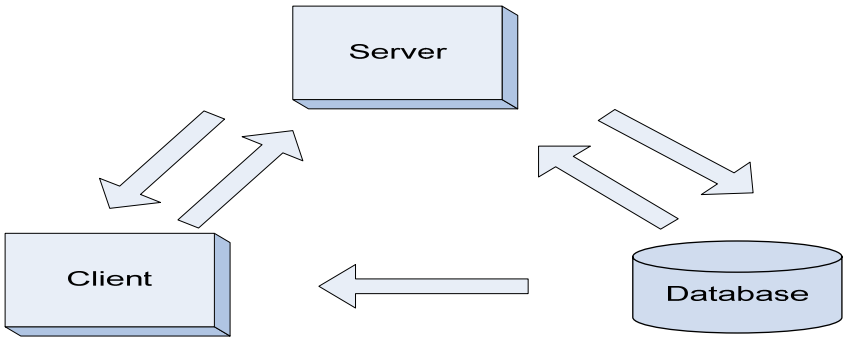


Figure 9. SESM Architecture

In the SESM environment, system designers input the information and constraints of the desired models. In Figure 9, the model engine captures the properties of logical models according to the designers’ commands and stores the logical models as the persistent model in the relational database. Designers can then view the corresponding visual model. In the SESM server, there is a translator which translates the system-theoretic model specification to XML or DEVSJAVA.

The translator can generate the partial simulation model, which after some extension to capture the behavior property, can run in a simulation environment. Currently, the SESM environment can generate a simulation code in DEVSJAVA. The primitive model in SESM is transformed into a DEVSJAVA atomic model and the composite model in SESM is transformed into a DEVSJAVA coupled model. The atomic model is partially generated and the coupled model is completely generated (in the sense to present the coupling relationship). DEVSJAVA models can be completed and simulated using the DEVSJAVA simulation engine as shown in Figure 10. By analyzing

the simulation results coming from DEVSJAVA, the designer gains a much better understanding about which design solution is the desired one based on the results of the simulation models. The whole process discussed above is very important to designers for decision making. It helps them choose the better alternative model for the system.

The logical model is designed as the visual model, and saved in database as the persistent model. With the translator, the logical model can be transformed into the simulation model which runs in the simulation engine. The modeling transformations in SESM are shown in Figure 10.

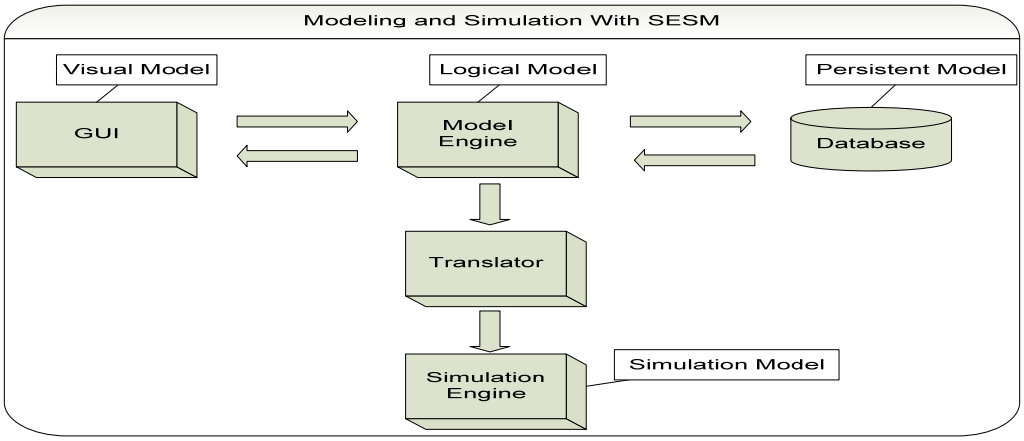


Figure 10. Modeling and Simulation with SESM

3.1.2 Model Example

A simplified AntiVirus system is illustrated here in SESM to show how SESM can be used to design models. An Anti-Virus system is intended to protect a network of computers from potential virus attacks. The primary objective of this system is to keep the computers on the network secured and virus-free. A simplified model of an AntiVirus system consists of a detectUnit and a killUnit. The detectUnit aims to find a virus and

sends it to the killUnit. The killUnit then kills the virus and sends the clean file out. If there is no virus, the detectUnit will send the file out.

The following is the detectUnit logical model example using the DEVS specifications:

Inports = {in, alertSignal}

Outports = {out, outVirus}

States = {idle, busy}

External transaction function: receive files and detect virus;

Internal transaction function: change state;

Output function: send out virus or clean files.

The user of SESM first designs the logical model of the primitive model: detectUnit and killUnit, as shown in Figure 11.

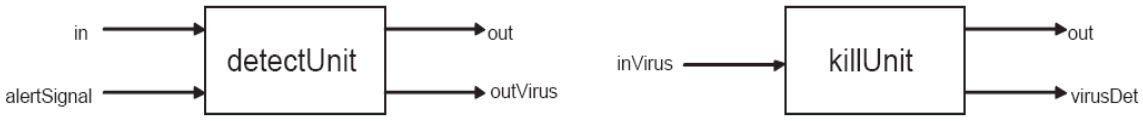


Figure 11. Visual Model of detectUnit and killUnit

With these two primitive models, a composite AntiVirusSystem can be built in SESM, as shown in Figure 12. The input/output variables can be added into the model input/output ports. SESM also supports non-simulatable models which are models can be defined in DEVSJAVA but cannot be simulated. An example is the model containers.

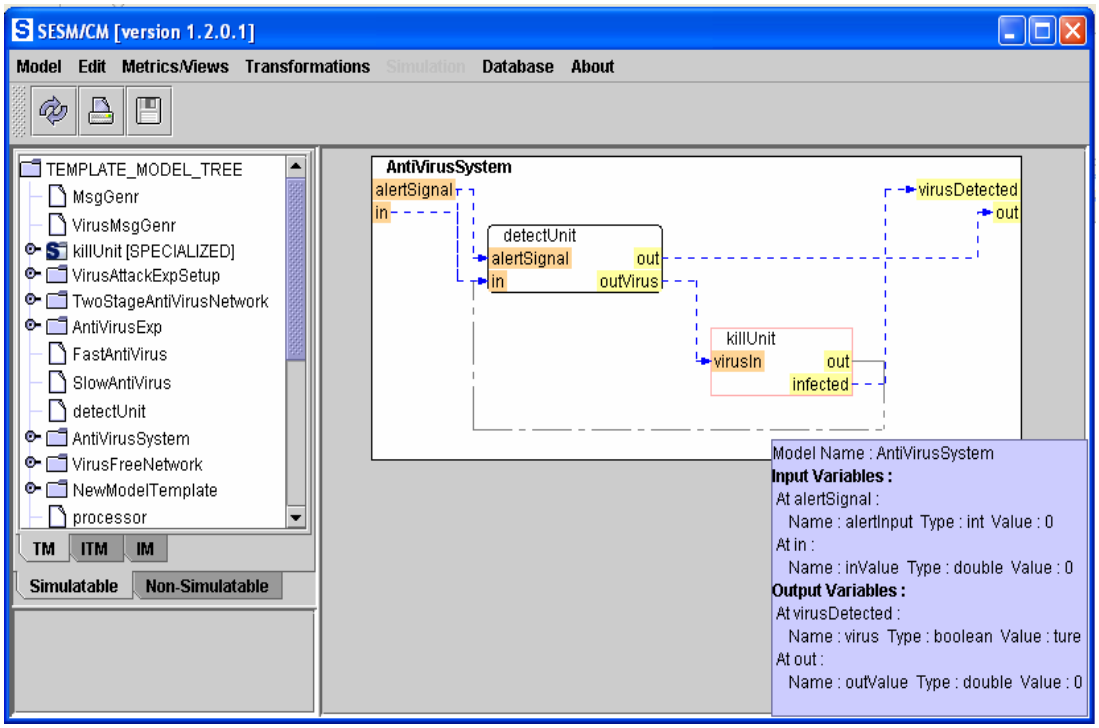


Figure 12. Template Model of WorkStation Composite Model

Figure 13 presents the persistent model of the example. The "tID" is the model ID, and the tModelType shows whether the model is an atomic model or a coupled model. The createTime shows the time when the model is created (which is a time period from a particular time to the time that the model is created.)

	tID	tModelType	createTime
+	AntiVirusExp	COUPLED	1.0897503E+12
+	AntiVirusSystem	COUPLED	1.1240470E+12
+	detectUnit	ATOMIC	1.124047E+12
+	DOC	COUPLED	1.1568941E+12
+	DOCOSM	COUPLED	1.1569786E+12
+	FastAntiVirus	ATOMIC	1.1240469E+12
+	HardwareLayer	COUPLED	1.1569783E+12
+	killUnit	SPECIALIZED	1.0897501E+12

Figure 13. Persistent Model

Given the persistent model support, SESM also provides structural complexity metrics for the system model. A simple example for the WorkStation in the AntiVirus system is shown in Table 5. The value in the metrics gives the name and type of the model and the number of model attributes.

Table 5

SESM Structural complexity Metrics

Attribute	Value
Model Name	AntiVirusSystem
Model Type	Composite
Children	
Immediate	2
Total	2
Ports	
Input	2
Output	2
Total	4
Couplings	
Internal	2
External input	2
External output	2
Total	6

With the structural complexity metrics, we can obtain information such as how many primitive models the system has, how many composite models the system has, and how many couplings the system has. Through the translator, the modeler can have the XML specification of the model and DEVSJAVA source code template of the model, as shown in Table 6.

Table 6

XML and DEVSJAVA Code Generated In SESM

XML detectUnit Model

```
<model>
   <atomicModel name="detectUnit">
      <inport name="alertSignal">
         <inportVariable name="alertSignal">
            <inportVariableType name="entity">
<inportVariableValue>alertInput</inportVariableValue>
            </inportVariableType>
         </inportVariable>
      </inport>

      </inport>
      <outport name="out">
         <outportVariable name="out">
         …….
```

DEVSJAVA detectUnit Model

```
public class detectUnit extends ViewableAtomic{
  public Processor(){
        this("detectUnit", 0.0);
  }
  public detectUnit (String name, processing_time){
        super(name);
        this.processing_time = processing_time;
        addInport("alertSignal");
        addInport("in");
       ……...
```

SESM can be used to design models but it does not distinguish between the software model and hardware model in a system. It is difficult for the modeler to design a software model and a hardware model separately. The lack of separation of software models and hardware models puts limitations on the application of SESM in co-design system modeling. For example, in the previous AntiVirus system, the detectUnit created in SESM does not tell people whether it is software (a software application for detecting

viruses like the Norton antivirus system) or hardware (an antivirus firewall). This brings problems when modelers add state variables or input/output ports into the model. For example, if the detectUnit is a software model, then how much memory the software requires should be added as a state variable. However, if it is a hardware model (the firewall) then the processing speed and bandwidth should be a concern. In co-design system modeling, it is important to extend SESM to systematically model the software and the hardware.

3.2 Discrete Event System Specification

Discrete Event System Specification (DEVS) is the specification for presenting the structural and behavioral property of discrete event systems. With the popularity of applications of computers in system engineering, discrete event modeling becomes an attractive formalism due to its relationship with digital computing (Sarjoughian & Cellier, 2001; Zeigler, Praehofer, & Kim, 2000).

3.2.1 Concepts and Approach

DEVS classifies models as one of the two types: the atomic model and the coupled model. The atomic model presents the basic level of DEVS formalism with specifications of the basic components of the system. The coupled model, which is composed by at least one atomic model and coupling relationship among these models, realizes the compositional constructs for structuring DEVS models into system structure hierarchies. Both atomic and coupled models can be simulated using sequential computation or various forms of parallelism. In a DEVS atomic model, there are five

methods (external transaction function, internal transaction function, confluent function, output function, and the time advanced function) which handle the state changes within the atomic model. The DEVS coupled model designates how (less complicated) models can be coupled together and how they interact with each other. The specificaiton of DEVS is in following structure:

$$M = <X, S, Y, \delta_{int}, \delta_{ext}, \delta_{con}, \lambda, ta>$$

Where

X is the set of input values

S is a set of states

Y is the set of output values

δ_{int}: $S \rightarrow S$ is the internal transition function

δ_{ext}: $Q*X^b \rightarrow S$ is the external transition function, where

$Q = \{(s, e) | s \in S, 0 \leq e \leq ta(s)\}$ is the total state set

e is the time elapsed since last transition

δ_{con}: $Q*X^b \rightarrow S$ is the confluent transition function

λ: $S \rightarrow Y$ is the output function

ta: $S \rightarrow R^{+}_{0,\infty}$ is the time advance function

As the basic model unit, the atomic DEVS model defines the states and the associated time bases. The DEVS coupled model designates how systems can be coupled together. A typical model in DEVSJAVA has two sets of input/output ports: input ports and output ports. Briefly, the external transition function dictates the model's new state

when an external event occurs (input coming from the input ports). The internal transition function dictates the system's new state when no event occurred since the last transition. The output function generates output through output ports and the confluent transition function decides the next state in case of collision between external and internal events. The time advanced function tells how long the model would stay in the current state if left without interruption.

3.2.2 DEVSJAVA Simulation Environment

Many implementations of the DEVS framework have been developed in popular programming languages including Java. DEVSJAVA is a Java implementation of DEVS specification. The DEVSJAVA 2.7 and 3.0 environments (in this dissertation the DEVSJAVA 3.0 will be used) are new generations of DEVS-based modeling and simulation environments that separate the modeling and simulation engines and the user interface. These environments offer new capabilities not found in DEVSJAVA 2.63, such as model type discovery and run-time execution using a logical clock or a wall clock (Cho, Zeigler, Cho, & Sarjoughian, 2000). DEVSJAVA 2.7 and 3.0 offer strong separation between modeling and simulation engines. This is important for supporting distributed simulation using alternative technologies such as CORBA (Object Management Group, 2005) and HLA (Institute of Electrical and Electronics Engineers, 2000). One of the key DEVSJAVA Application Programming Interfaces (APIs) is GenCol which provides the collections for models (Park, Zeigler, & Sarjoughian, 2001) . Table 7 shows the important modules in DEVSJAVA and each of their purposes.

Table 7

DEVSJAVA 3.0 Modules

Module	Purpose
GenCol	non-simulation structure modeling
genDevs.modeling	atomic and coupled model specification
genDevs.simulation	abstract atomic and coupled simulator specification
simView	simulation visualization

DEVSJAVA 3.0 provides the API which contains the base class entity, that serves as the root class for the *modeling* (genDevs.modeling), *simulation* (genDevs.simulation), and *visualization* (simView) modules (Park, Zeigler, & Sarjoughian, 2001). This module provides more collection facilities than the Java Development Kit (JDK) 5.0 collection API. GenCol has its own container classes using the entity class from the Container library from DEVSJAVA 2.6.3, as shown in Figure 14. Figure 15 presents the classes in GenCol and their relationships. The combination of Java Collection API and GenCol APIs, therefore, offer all of the functionality that was in Container API used in DEVSJAVA 2.6.3 as well as others needed for the new *modeling* and *simulation* packages in DEVSJAVA 3.0. DEVSJAVA 3.0 also provides interfaces for designing alternative models with different behaviors.

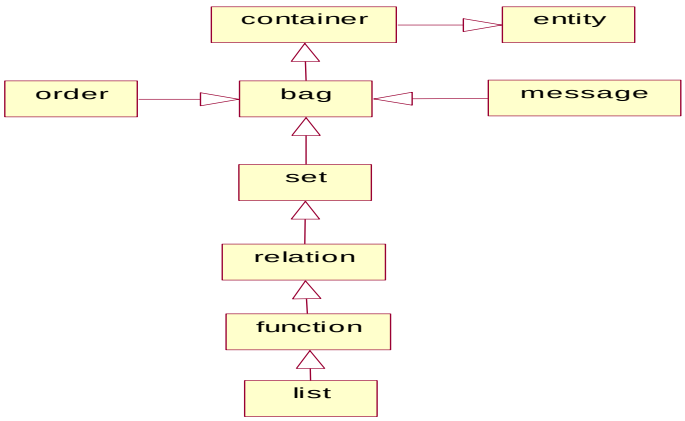


Figure 14. DEVSJAVA 2.63 Container Specification

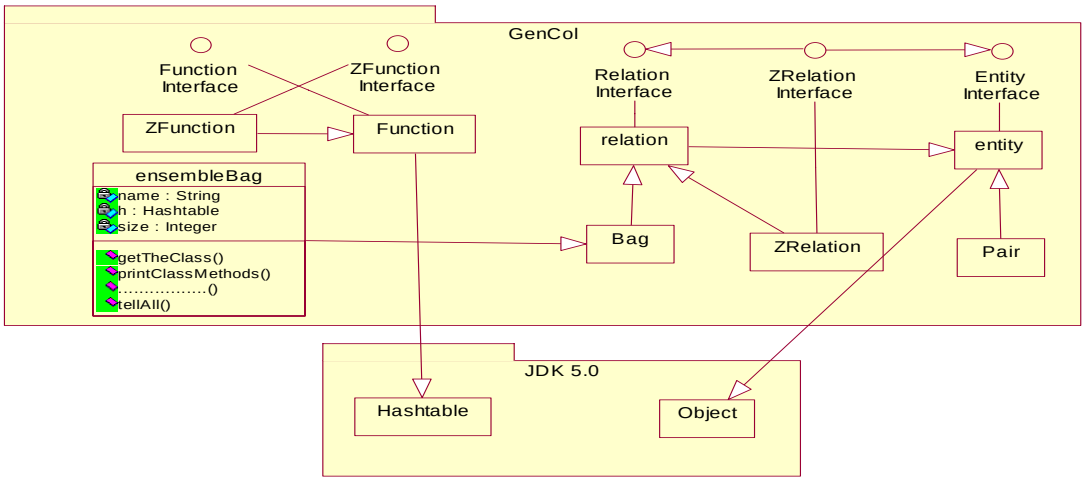


Figure 15. GenCol Container Specification

In DEVSJAVA 3.0, the modeling module provides basic modeling elements including atomic and coupled models such as the base class devs. The devs class extends class entity with methods to add input and output ports so that a model can send and receive messages. Extending from devs, the atomic class provides state assignment and functions to process external and internal events. With DEVSJAVA 3.0, all atomic models can run as a separate component with the viewableAtomic and all coupled models

can be executed as a separate system with viewableDigraph (as shown in Figure 16). The other basic modeling elements in the modeling module are ports and coupled, which allow coupling of atomic and coupled models.

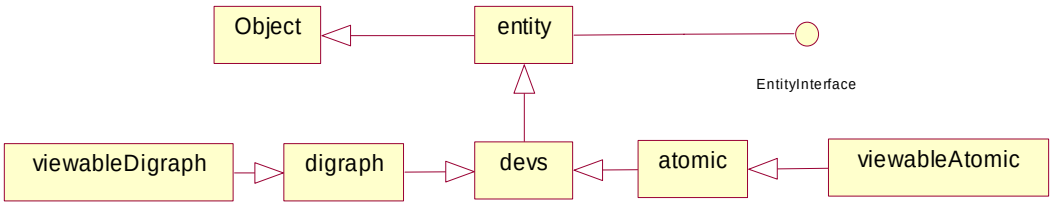


Figure 16. viewableAtomic and viewableDigraph

Similar to the *modeling* module, the *simulation* module contains classes that execute the atomic and coupled models which includes the transmission of messages. The classes in the simulation package are realizations of the DEVS parallel abstract simulator (Arizona Center for Integrative Modeling and Simulation, 2007). The atomicSimulator and coupledSimulator are two of the key classes for handling the timing of atomic and coupled models and their exchange of output and input events. The simulator design is shown in Figure 17.

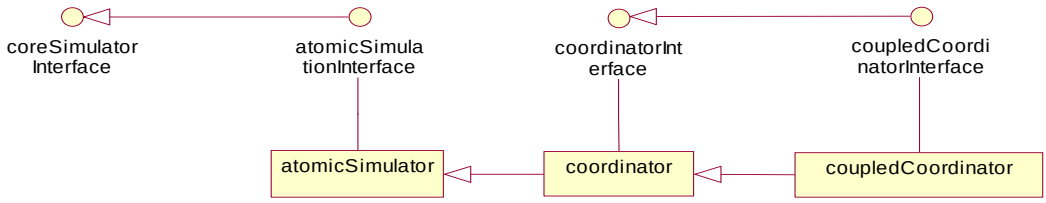


Figure 17. Simulator Utilities

Figure 18 shows another aspect which cannot be found in DEVSJAVA 2.63, the visualization module. The module is supported by the *SimView* package, which provides services for visualizing the simulation of the atomic and coupled models (viewableAtomic

and viewableCoupled), configuring simulation models, and executing and viewing the simulation dynamics.

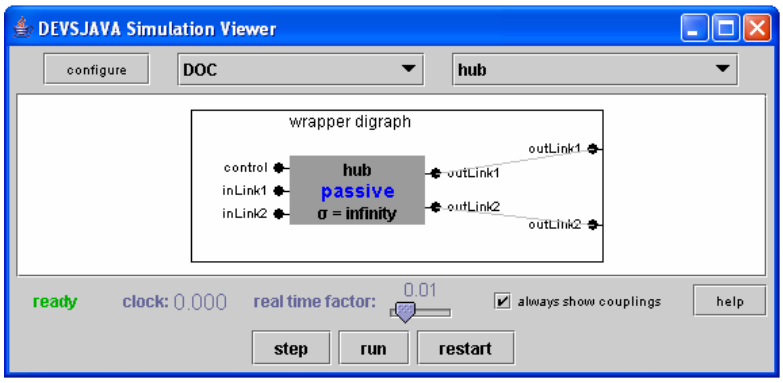


Figure 18. Graphical View of An Atomic Model in DEVSJAVA 3.0

As an example, an atomic LCN model called *hub* is depicted in DEVSJAVA in Figure 18. This DEVSJAVA Simulation Viewer generated by *SimView* has two functionalities: model display and simulation control. As shown in Figure 18, a user uses the "configure" button to choose the model packages. "DOC" and "hub" at the top of Figure 18 shows that the "hub" model in "DOC" package is chosen for display. In the middle part of the simulation viewer is the display of the chosen model. A model component can receive input messages on one or all of its input ports (e.g., inLink1) and concurrently produce output messages on its output ports (e.g., outLink2). The states of the hub atomic model (e.g., execution phase (passive) and the duration in which the hub stays in phase passive (∞)) can be viewed at run time. The execution speed of the hub can be controlled via the "real time factor". The "step", "run" and "restart" buttons in the bottom of the simulation viewer are for the simulation control purposes. The "step" button can show the single simulation step based upon a single simulation event.

3.2.3 Simulation Model Example

The AntiVirus system in Section 3.1.2 is illustrated here for the DEVSJAVA framework. The AntiVirus system is an anti-virus network system including a "detectUnit" model to detect virus messages passing into it, and a "killUnit" model which can get rid of the virus messages. These two models compose a coupled model, the "AntiVirusSystem". Table 8 shows samples of the DEVSJAVA source code for both the atomic model "VirusProcQ" and the coupled model "AntiVirusSystem".

Table 8

DEVSJAVA AntiVirusSystem Source Code

Atomic Model: detectUnit

```
public class VirusProcQ extends ViewableAtomic {
  protected entity job1;
  protected entity jobx;
  protected Queue q;
  public VirusProcQ(String name) {
        super(name);
    addInport("inVirus");
    addOutport("out");
    addOutport("virusDet");
  }
public void initialize() {
    q = new Queue();
    phase = "passive";
    sigma = INFINITY;
    job1 = new entity("nil");
    super.initialize();
  }
  public void deltext(double e, message x) {
    Continue(e);
    if (phaseIs("passive")) {
      for (int i = 0; i < x.getLength(); i++) {
        if (messageOnPort(x, "inVirus", i)) {
          job1 = x.getValOnPort("inVirus", i);
          Random ra = new Random();
……
```

Coupled Model: AntiVirusSystem

```
public class SimpleVirusNet
```

```
    extends ViewableDigraph {
  public SimpleVirusNet() {
    super("AntiVirusSystem");
    addInport("in");
    addInport("alertSignal");
    addOutport("out");
    addOutport("virusDetected");
    ViewableDigraph rv1 = new RouterVirus("detectUnit", "detectproc");
    ViewableDigraph rv2 = new killUnit("killUnit", "killproc");
    add(rv1);
    add(rv2);
    initialize();
    addCoupling(this, "in", rv1, "in");
    addCoupling(this, "alertSignal", rv1, "alertSignal");
    addCoupling(this, "alertSignal", rv2, "alertSignal");
    addCoupling(rv1, "out", rv2, "in");
    addCoupling(rv1, "outVirus", rv2, "virusin");
.....
```

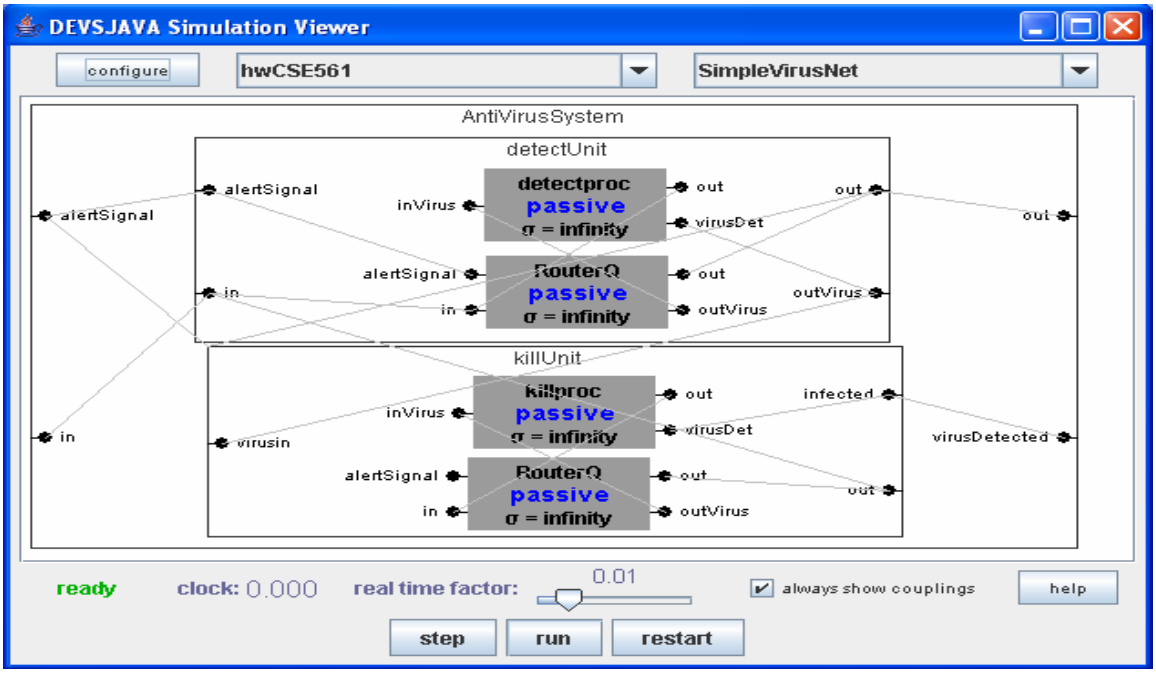


Figure 19. AntiVirusSystem Simulation View in DEVSJAVA GUI

DEVSJAVA 3.0 also provides a GUI where the user can run the simulation. Figure 19 is the AntiVirusSystem in the simulation view of DEVSJAVA. DEVSJAVA provides the system designer a framework to code their model with a general purpose

programming language and run simulations for their model. It requires designers be familiar with DEVS specification and have Java programming skills. DEVSJAVA does not provide multiple aspects of a model, and does not provide mechanisms to manage the view of a large-scale system model for designers. The models in DEVSJAVA do not have the separation between a software model and a hardware model. For example, in the above AntiVirus System, the detectUnit and killUnit could be described as both software and hardware. The lack of separation of a software layer and a hardware layer has the following problem: it is difficult for the designer to quickly design software and hardware with the concerns for the unique properties of software and hardware.

3.3 Distributed Object Computing Modeling Approach

Distributed Object Computing (DOC) methodology is presented by James M. Butler (Butler, 1995). DOC provides a conceptual basis for modeling distributed object computing systems as a set of software components mapped onto a set of networked hardware nodes.

3.3.1 Abstract Model

DOC provides three abstractions to model a system's software and hardware layers and their interactions. The software layer is captured as a distributed cooperative object (DCO) model. The hardware layer represents a loosely coupled network (LCN) model of processing nodes, network gates, and interconnecting communications. These enable the distributed cooperating software components to interact. The distributed DCO software

assigned to LCN hardware forms an object system mapping (OSM) (Butler, 1995). The architecture of DOC is presented in Figure 20.

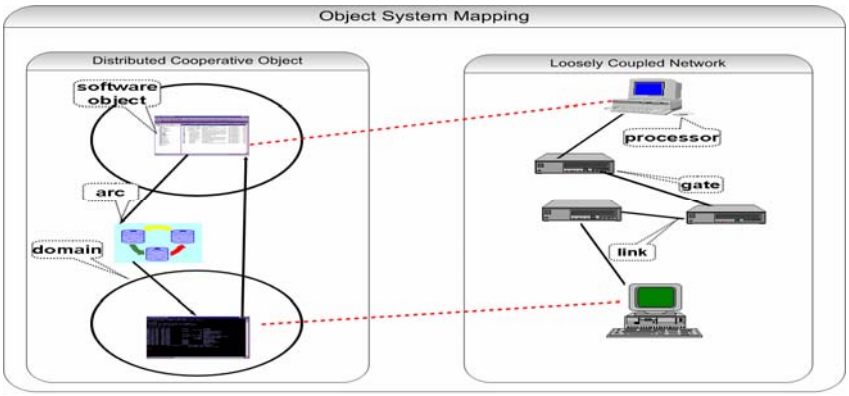


Figure 20. Distributed Object Computing Approach

The fundamental concept in DOC is the separation of software and hardware components, which sets up the layered-structure, and the mapping from one layer (software layer) to another layer (hardware layer). The DCO software abstraction is described in terms of computational domains, software objects, message arcs, and invocation arcs. In a computational domain, there is a set of software objects that comprise an independent executable program. Following the traditional object-orientation concept, software objects in DCO represent software components which are composed of data members (attributes) and functions (methods) that operate on the attributes. Invocation arcs in DOC define client–server type software object interactions. Message arcs define peer-to-peer type software object interactions. The representation for DCO is a 9-tuple set *S* containing a set *D* of domains, a set *T* of software objects, a set *A* of directed invocation arcs, a set *G* of directed message arcs, and mapping functions *u, v, x, y,* and *z*. Function *z* maps software objects of *T* onto a set of domains *D*. Functions *x* and

y map the calling ends of invocation arcs *A* onto software objects of *T* and the target ends of *A* onto a power set of *T*. Functions *u* and *v* map the source ends of message arcs *G* onto the software objects of *T*. Following is the equations specification of DCO. The details of these equations can be found in (Butler, 1995):

$$S \equiv (D, T, A, G, u, v, x, y, z)$$

$$u : \gamma \rightarrow \tau \; ; \; \gamma \in G, \; \tau \in T$$

$$v : \gamma \rightarrow L; \; \gamma \in G, \; L \subseteq T, \; |L| \geq 2$$

$$x : \alpha \rightarrow \tau; \; \alpha \in A, \; \tau \in T$$

$$y : \alpha \rightarrow L; \; \alpha \in A, \; L \subseteq T, \; L \neq \emptyset$$

$$z : \tau \rightarrow L \; ; \; \tau \in T, \; L \subseteq D, \; L \neq \emptyset$$

The software object has a working mode parameter that defines its multi-threaded behavior: *none*, *object*, or *method*. This working mode determines the level of execution concurrency the software object supports. At the *none* level, only one request per object may execute at a given time; each additional request to the object gets queued. At the *object* level, only one request per method may execute concurrently; additional requests against an executing method get queued. At the method level, all requests to the software object may execute concurrently (Butler, 1995; Hild, 2000; Hild, Sarjoughian, & Zeigler, 2002).

The LCN hardware representation of networks system results in the specifications of processors, routers, and links. LCN processors are capable of performing computational work for DCO software objects and transmitting and receiving software object interaction messages by providing computational resources (CPU, memory,

bandwidth, buffer size, etc). LCN routers interconnect two or more network links and operate in one of two modes, a network router and a network interface of a processor. In an LCN router, packet address information is used to make routing decisions and switch a packet down a specific link. LCN links provide a communication path between processors and routers. The mathematic representations of LCN can be described as a 5-tuple set *H* containing a set *P* of processors, a set *K* of network gates, a set *N* of network links, and mapping functions *f* and *g* of processors and gates, respectively, onto a power set of network links. This representation is summarized in the following equations (Butler, 1995):

$$H \equiv (P, K, N, f, g)$$

$$f : \pi \rightarrow L; \quad \pi \in P, \; L \subseteq N, \; L \neq \emptyset$$

$$g : \phi \rightarrow L; \quad \phi \in K, \; L \subseteq N, L \neq \emptyset$$

DCO concepts provide the layer of the target software architecture. LCN concepts provide the layer of the target hardware architecture that imposes time and space constraints, but lacks a specification of dynamic behavior. So, individually, neither of the two layers can provide the value in modeling the structure and behavior of a distributed object computing system. The third concept in DOC is the Object System Mapping (OSM), which refers to the mapping from the DCO layer onto the LCN layer. By this layer-to-layer mapping, the abstract behavior dynamics of the software layer are combined with and constrained by the capacity of the resource and the topology of the hardware layer and the hardware is related to the model dynamic behavior. With OSM, the software layer and hardware layer can work together to specify the model's structure

and behavior properties. The mathematical OSM representation is a 5-tuple set Ψ containing an LCN representation *H*, a DCO representation *S*, a set of communication modes *C*, and mapping functions λ and μ. Function λ maps DCO software objects T_s onto LCN processors P_H. Function μ maps DCO invocation arcs A_s and message arcs G_s onto communication modes *C*. A communication mode *c* is defined by random variables representing packet size *P*, packet overhead *V*, and acknowledgment packet size *R*. This representation is summarized in the following four equations for which, details can be found in (Butler, 1995):

$$\Psi \equiv (H, S, \lambda, C, \mu)$$

$$\lambda : \tau \rightarrow \pi; \quad \forall \tau \in T_s, \ \pi \in P_H$$

$$c = (P, V, R); \ c \in C, \ P > V \geq 0, \ R \geq 0$$

$$\mu : \omega \rightarrow c; \quad \forall \omega \in \{A_s \cup G_s\}, \ c \in C$$

DOC methodology provides a layered solution for large-scale network systems design and analysis. With the separation of the software layer and hardware layer, designers have more flexibility to design and analyze systems. To design and analyze the software components, the designer can keep the hardware layer unchanged, then the performance of different software components can be studied based on the same hardware configuration. Also, to study different hardware configurations, the same software can be kept to run in alternative hardware layers. This layered-structure not only decomposes the large-scale system to lower the structural complexity by layering, but also provides designers the ability to focus on the specific layer. The contribution or the limitation to the system performance from the software layer or the hardware layer can be

studied separately. This allows the designer choose the “better” software or hardware components so that a “better” design solution can be made.

3.3.2 DEVS Realization of DOC

As the first implementation of DOC using DEVS, DEVS/DOC 1.0 was created at the in University of Arizona (Hild, 2000; Hild, Sarjoughian, & Zeigler, 2002). The latest version of DOC implementation is DEVS/DOC 2.0 modeling and simulation environment. The DEVS is used to develop the specifications of DOC components, then these specifications are implemented by DEVSJAVA 3.0 and the experimental frame concept is used to define the simulation experiments (Hu & Sarjoughian, 2005).

In DEVS/DOC, essentially, DOC provides the layered architecture concept for distributed object computing. DEVS formalism provides a system theoretic basis for specifying component behaviors in distributed object computing. DEVSJAVA enables object-oriented modeling, concurrent simulations, and web-enabled simulations. The Java technology makes the models in DEVS/DOC have well-defined inheritance hierarchy relationship. This helps designers describe models using UML so that DEVS/DOC has the potential to work with other standard modeling and simulation framework such as the Eclipse Modeling Framework (EMF). Also, the polymorphism brought by DEVSJAVA enables DEVS/DOC to have different configurations on the same model at the same time so that the modeler can reconfigure the network easily. DEVSJAVA gives DEVS/DOC the object-oriented advantages for modeling and simulation use. In DEVS/DOC building

blocks, there is an experimental frame concept to provide a formal structure when specifying the simulation performance to be observed for analysis.

The UML shown in Figure 21 shows the relationship between DEVSJAVA and DOC and some of the detailed design in DOC elements. These conceptual constructs, DOC, DEVS, and Java, are harmoniously combined together to provide designers a better way to design and analyze better network systems in an easy way. By providing a layered-structure, DEVS/DOC lends itself as a sound environment for the modeling and simulation of network systems.

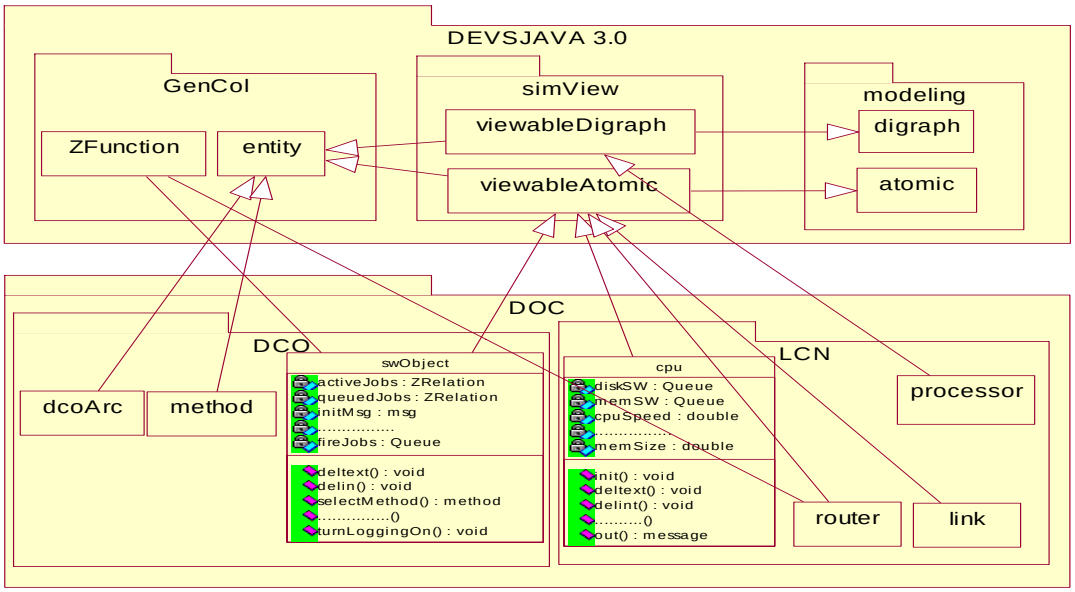


Figure 21. DEVS/DOC Structure

3.3.3 Network System Simulation with DEVS/DOC

The AntiVirus System example is also implemented in DEVS/DOC to illustrate the unique features of the layered-structure, as shown in Figure 22 and Table 9. In Figure 22, the detectUnit and killUnit in Figure 12 is defined as detectSoftware1 and

killSoftware. These two software applications run in the same hardware AntiVirusProcessor.

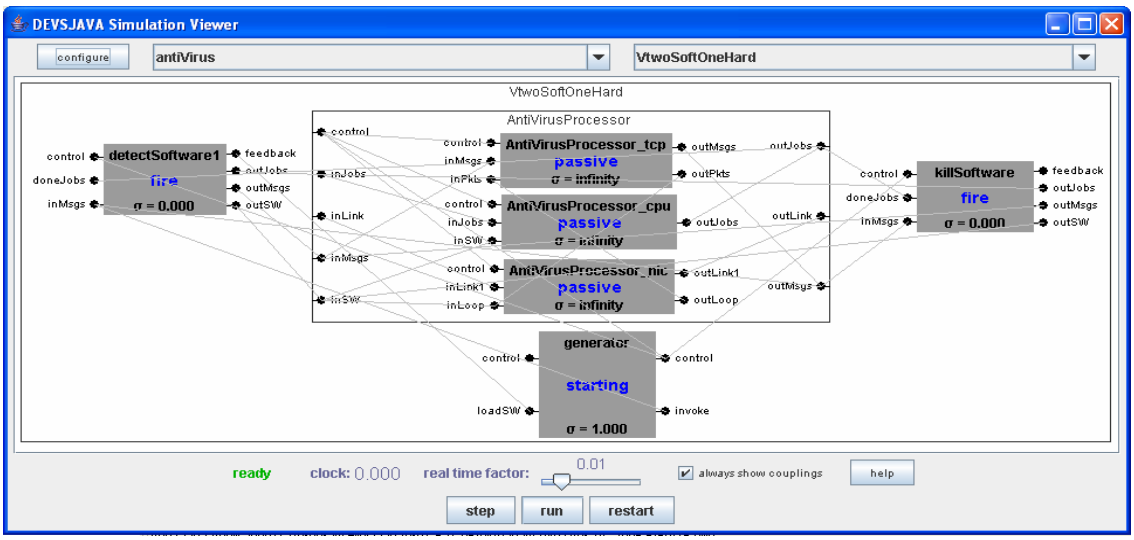


Figure 22. AntiVirus System Example with DEVS/DOC

This separation of the software and hardware model make it much easier for the modeler to design different features of the model such as the software model needs to have the required memory size and the hardware model needs to have the CPU speed. This is both for the state variables and the functions. Without the separation of the software and hardware, it is hard to define the functions in models. The function shown in the software model in Table 9 cannot be visually supported by SESM.

Table 9

DEVSDOC AntiVirusSystem Source Code

Software

`public void deltext(double e, message x) {`
`  if (!timerMsgs.isEmpty())`
`  holdIn("active",timerMsgs_reset(e));`
`  String M="", nl='\n'+"  ";`
`  for (int i=0; i<x.getLength();i++) {`
`  if (messageOnPort(x,"doneJobs",i)) {`

```
       job doneJob = (job)x.getValOnPort("doneJobs",i);
         if (this.eq(doneJob.get_swObjectName())) {
              doneJob.toString();
              int workLeft = doneJob.get_workLeft()
```

Hardware

```
public processor(String N, double HS, double LS, double BW, double BS,
double CS, double MS, int MPS) {
             super(N);
             atomic CPU = new cpu(N+"_cpu", CS, MS);
              add(CPU);
       make(N, HS, LS, BW, BS, MPS, CPU);
}
public void make(String N, double HS, double LS, double BW, double BS,
int MPS, atomic CPU) {
        addInport("inLink");
        addInport("inMsgs");
        addInport("inSW");
        addInport("inJobs");
        addInport("control");
        addOutport("outLink");
…..
```

DEVS/DOC is not devised for simulating embedded systems which focuses on one piece of software running in one piece of hardware. DEVS/DOC is a simulator for a distributed computing system which handles multiple pieces of software interacting with multiple pieces of hardware. However, DOC does not provide a view of different resolutions for the designer according to different system decompositions. Also, DOC does not provide a database interface, and it does not provide a friendly graphic modeling tool for the designer to use.

Large-scale network simulation is important today (Riley & Ammar, 2002). Like other simulation tools such as NS-2, DEVS/DOC can help to create user-defined protocols for existing models. In DEVS/DOC, the *network interface* class and the *link*

class provide the CSMA/CD (Carrier Sense Multiple Access with Collision Detection) protocols (Tanenbaum, 1996) for the network model.

CSMA/CD protocol varies with different back off schemas. (When there is a collision in the media, the nodes will wait for a particular time to send their packets again. This kind waiting is called back off. The length of the waiting time depends on what schema the node uses) (Tanenbaum, 1996). The three different back off schemas that will be briefly described in this chapter are: the random back off schema (RBO), the one by one back off schema A (OBOA), and the one by one back off schema B (OBOB). RBO, also called "Binary Exponential Back off Schema" is the most popular one used in IEEE 802.3 (Ethernet). The key algorithm states that after n collisions, a random number between 0 and 2^n -1 slot is chosen for the retransmission.

In Figure 23, a shared bus network topology is used to show the capability of DEVS/DOC to handle network systems. The clients send requests to the server through the Hub-ethernet and the Link. The server responds to the request and sends it to the clients.

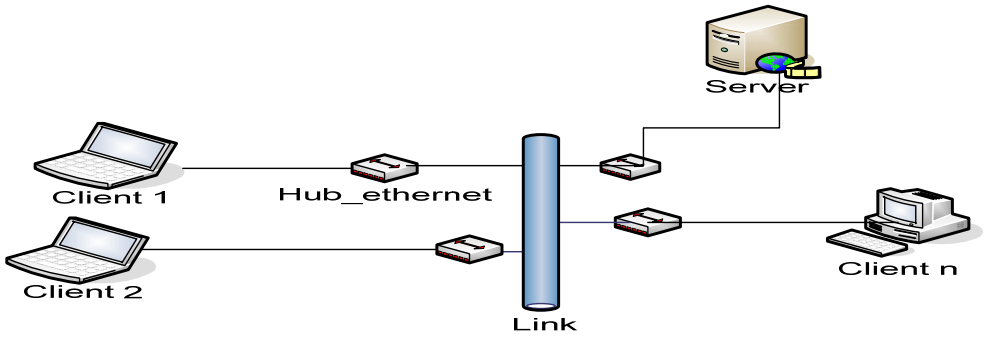


Figure 23. Shared Bus Topology

With the hardware support set to a 2.4GHz CPU and 1GB of memory, the maximum number of nodes (server and client) is 1000 (1 server and 999 clients). Table 10 shows the configurations of the simulation models.

Table 10

Selected Hardware, Software, and Experimentation Components

Hub Ethernet	*Attribute*	*Value*	*Unit*
	ethernet speed	10^6	bit/sec
	processor internal bandwidth	infinity	bit/sec
	buffer size	infinity	bit
Processor	*Attribute*	*Value*	*Unit*
	cpu speed	10^8	operations/sec
	cpu memory size	$64*10^6$	bytes/sec
	maximum packet size	$31*10^3$	bit
	processor internal bandwidth	infinity	bits/sec
	processor network interface speed	$2*10^9$	bits/sec
	buffer size	infinity	bit
	packet header size	20	byte
Software	*Attribute*	*Value*	*Unit*
	size	$2*10^6$	byte
	self-starting duty cycle	infinity	sec
	thread mode	none/method	
Acceptor	*Attribute*	*Value*	*Unit*
	time for discovering LCN topology	1	sec
	number of times to invoke task	1	NA

The performance of the BEBS, OBOA and OBOB CSMA/CD protocols is strongly affected by the scale of network tremendously. Their performance and analysis are discussed in (Hu & Sarjoughian, 2005).

3.3.4 Discussion of Network System Simulation Tools

As mentioned in Chapter 2, there are a variety of simulation environments, such as NS-2, GloMoSim, OPNET, and QualNet (Global Mobile Information Systems Simulation Library, 2005; Information Sciences Institute, 2004; Jaikaeo & Shen, 2005; OPNET Technologies, 2004) that support the modeling of computer networks. The most important difference between DEVS/DOC and other simulators is that DEVS/DOC provides the specifications for the separation and integration of the software and hardware models. This helps DEVS/DOC model and simulate the software activities in the network application layer (Tanenbaum, 1996). This separation also provides the possibility that modeler can configure and consider multiple design options of the software and hardware models separately and together.

As a discrete event modeling and simulation environment, DEVS/DOC shows its strengths. For example, as we discussed in Chapter 2, although NS-2 provides many detailed prebuilt models, there is a strong dependency among some of the NS-2 modules. This makes it challenging to model new protocols or to make changes to existing protocol models. That is, given its complexity and low-level detailed models, it is necessary to have the knowledge of NS-2 at the software implementation and design levels for serious simulation (Information Sciences Institute, 2004). DEVS/DOC is similar to other environments such as NS-2 and provides modelers with ready-to-use hardware modules such as the *cpu*, the *router*, and the *link*. However, unlike NS-2 and others such as OPNET (OPNET Technologies, 2004) which also provides many detailed prebuilt

models, it provides greater flexibility and simplicity for creating customized hardware modules as well as software modules and then composing them within a well-defined simulation framework. DEVS/DOC is designed for modeling and simulating the hardware and the software of a network separately. This makes DEVS/DOC better suited than other simulations tools for integration of hardware and software simulation modeling.

From a usability aspect, DEVS/DOC provides detailed state information for all of the components in the networks, including the interaction between them, concurrently. Thus, the user can observe and analyze the dynamic interaction relationship among network components at any given logical state. With NS-2, it is difficult because it is hard to give a continuous spotlight to the state information in NS-2.

Like some other simulation environments such as GloMoSim (Global Mobile Information Systems Simulation Library, 2005), DEVSJAVA 3.0 provides the control function in its GUI part where a modeler can choose models, set up simulation parameters (such as the time factor) and execute the simulations. The simulation view in DEVSJAVA 3.0 is important. It is one of the functionalities that makes DEVSJAVA 3.0 distinguishable from other simulation environments. Through the view function, modelers can observe the status (the information such as the changing of state and local timing) of the component models at any time while the simulation is running. In other simulation environments such as NS-2, this kind of information can be obtained in the log file after the simulation is complete (Information Sciences Institute, 2004; Shaukat & Sarjoughian, 2007). Moreover, the interactions among the model execution can be

observed dynamically in DEVS/DOC. This provides a better understanding of the relationship between models. It is difficult for other simulation environments such as NS-2 to provide this feature (Information Sciences Institute, 2004). Another important feature of DEVS/DOC is that the modeler can use other model environments such as SESM (Scalable Entity Structure Modeler) (Cyberspace Center, 1997) to design the model and then automatically generate partial DEVS/DOC code, which can be run using a DEVS simulation engine. The comparison of NS-2 and DEVS/DOC indicates that the latter is more suitable for system-level network simulations and experimentations with user friendly interfaces.

3.4 Summary

This chapter describes some details of the SESM modeling framework, DEVS formalism, DEVSJAVA simulation environment, and the DOC abstract model. The study highlights SESM's visual modeling, model storage, and structural complexity measurement. However, SESM does not support co-design modeling. DEVS provides a specification for discrete event systems and DEVSJAVA provides a simulation engine with a dynamic simulation view. DEVSJAVA does not provide visual and persistent modeling and, for network co-design, it does not provide the specification to define the software and hardware models.

This chapter also presents one part of the work in this dissertation, DEVS/DOC, a modeling and simulation approach which is a realization of the DOC abstract model through DEVSJAVA 3.0. This work plays an important role in this dissertation in the

sense that it provides an environment for simulating the models designed in the SESM/DOC (which will be detailed in Chapters 4, 5, and 6). The simulation is necessary for evaluation dynamics of alternative design options for the software, hardware, and system models. An evaluation between DEVS/DOC and other network simulators is presented based upon the features provided to users and the simulation capability for the co-design of a network system, to illustrate the strengths and limitations of DEVS/DOC. The comparison shows that the capability to separate and synthesize software and hardware models makes DEVS/DOC strong in the network application layer modeling and simulation. However, it lacks the support for visual and persistent modeling and the measurement for co-design system structural complexity.

4 COMPONENT-BASED LAYERED STRUCTURE MODELING APPROACH FOR CO-DESIGN NETWORK SYSTEMS

In this chapter, a component-based layered structure modeling approach for a software and hardware co-design network system is introduced. The specifications to separate and synthesize the software and the hardware model layers will be given and the layered structure model types and the model constraints will be defined.

4.1 Co-Design Modeling Approach for Network Systems

We have seen that DEVSJAVA, SESM, and DEVS/DOC have their strengths in different aspects of modeling and simulation. Before they can be used in modeling a distributed co-design system, each of them needs to be extended.

Compared to traditional embedded systems, a distributed network system provides services through a network. A network system includes different kinds of hardware and different types of software applications. The interactions between the entities in the system are complicated. Consequently, the modeling approach for distributed co-design system needs to provide facilities to support model design for software models and hardware models separately. Also, it has to support the assignment of software models to hardware models which results in the overall system model.

Modeling and simulating a search engine network is both interesting and challenging. Distributed network topology is used by most of the popular search engines such as Google, Yahoo, and MSN. Developing these search engines entails overcoming difficulties such as workload balancing and performance (Hu & Sarjoughian, 2005) that are related to the search engines' software applications, hardware configurations, and

topologies. Modeling and simulation of the software and hardware parts in engine networks is important for analysis and design purposes. A search engine system can be described as a distributed network system. On the client side, the clients can use different hardware such as PCs, laptops, PDAs (Personal Data Assistants) and smart phones. On these hardware devices, different software applications can be executed to make different search requests such as text file search, video file search, and database queries. On the server side, the servers can be workstations, super computers, clusters, and server farms. On the server hardware, there are different software applications to provide different services to requests such as text file search service, database query service, and map search service. The communication between the server side and client side goes through the link and router hardware, as shown in Figure 24.

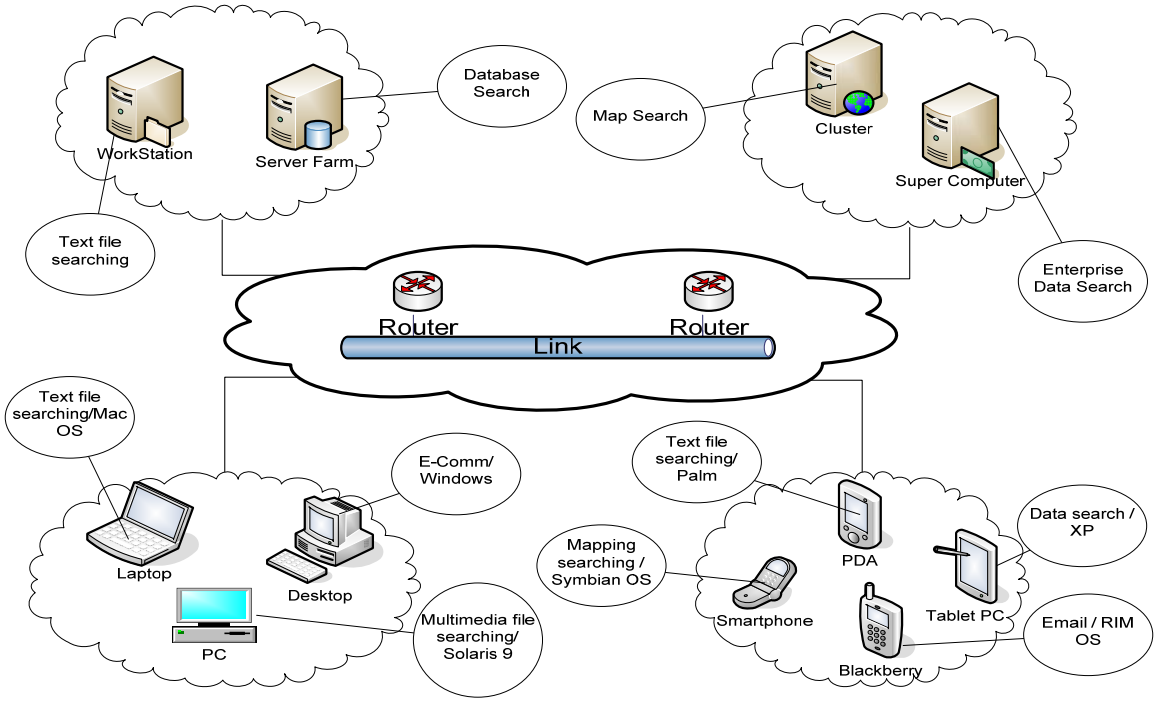


Figure 24. Distributed Co-Design Network System

This is a complex system, and there are many design choices for synthesis between the software and hardware components. Many factors affect network performance. Software applications require different kinds of resources. Alternative hardware protocols distribute the traffic in different patterns. Even a single ad hoc change of the hardware parameter will affect the network collision number, bandwidth utility, and system delay (Young, Cook, & Mahabadi, 2003). All of these affect the search engine network performance, which is key to identifying how fast the clients can get back the search results. When the search engine is running, all of the factors interact to make the system hard to analyze. To gain insight into the behavior of a particular network protocol, or hardware parameter set-up, or to gain a better understanding of how a particular search software model affects the whole system, an analysis of the system by separating the hardware and software layer is necessary.

This kind of complex distributed co-design system requires a powerful environment for its modeling and simulation. Given such a complex system, a modeler can benefit from the following capabilities:

1) separately representing software and hardware parts;
2) visually modeling the system parts and their synthesis;
3) supporting model repository and reusability;
4) providing measurements for structural complexity of all the models;
5) automatically generating simulation code.

These requirements are needed to specify software and hardware models separately within a particular set of constraints. This approach needs to be implemented

as a modeling environment that can ensure that the relationships among the logical models, the visual models, and the persistent models are properly handled. The integration of the SESM and the DOC models will lead to a distributed co-design modeling approach. In this chapter, the approach to specifying the multiple layer logical models will be described and used as the foundation of the proposed distributed co-design SESM/DOC tool.

4.2 Layered Structure Decomposition for Network Systems

To design distributed computing models, the software components and the hardware components must be separated. This raises the topic of layered structure decomposition. To understand the layered structure decomposition, let's look at the physical decomposition in SESM first.

4.2.1 Model Types in Scalable Entity Structure Modeling

Based on system theory and abstraction concepts, SESM describes a system in terms of TM, ITM, and IM (as discussed in Chapter 3). Each of these models uses the basic *is-a* and *has-a* relationships to define a system in terms of its components, composition, and specialization. In this chapter, we will introduce the logical model specification of the template model, instant template model, and the SESM axioms (Sarjoughian, 2001). These formalisms can be used for modeling both software and hardware layers.

Notations:

Model: m, n

Model Name: $m._{name}$

Model Structure: $m._{structure}$

Model Behavior: $m._{behavior}$

Model Ports *:* $m._{ports} = \{m_{port_1}, m_{port_2}, ..., m_{port_k}\}$

Decomposition: D(m)

Specialization : S(m)

Internal Coupling : $C(m._{PortOut}, n._{PortIn})$

External Coupling: $C(m._{PortIn}, n._{PortIn})$ or $C(m._{PortOut}, n._{PortOut})$

Isomorphic*:* $\cong$

Model Base (MB): A model base is a set of unique models. The uniqueness is based on the model name. A unique name in a model base can belong only to one model. Another way to understand this is to say that a model in a model base is distinguishable from other models in the same model base by a unique name. This is a "one-to-one" relationship. The model in a model base can be a primitive model or a composite model.

$MB = \{m \mid m._{name} \neq n._{name} \Leftrightarrow m \neq n, m, n \in MB\}$

In Chapter 3, we introduced three complementary types of models: the template model (TM), the instance template model (ITM), and the instance model (IM). We also saw the difference among the three types of models. The notations above work together with the three model types to provide modelers with different model resolutions. For example, the general model base can be divided into three distinct model bases for TM,

ITM, and IM ($MB_{TM,}$ MB_{ITM} and MB_{IM}). These model bases have different naming conventions. MB_{TM} has a one-level naming convention: the model name ($m._{name}$) in MB_{TM} is the model's name. MB_{ITM} has a two-level naming convention: the model name ($m._{name}$) in MB_{ITM} includes its template model name and the ID in the instance template model. MB_{IM} has a three-level naming system: the model name ($m._{name}$) in MB_{IM} includes the name for the instance template model and the instance model ID. The model base constraint shown above applies in each of these model bases.

$$MB_{TM} = \{m \mid m._{templateName} \neq n._{templateName} \Leftrightarrow m \neq n,\ n \in MB_{TM}\}$$

$$MB_{ITM} = \{m \mid (m._{templateName} + m._{instanceTemplateID}) \neq (n._{templateName} + n._{instanceTemplateID}) \Leftrightarrow m \neq n,\ n \in MB_{ITM}\}$$

$$MB_{IM} = \{m \mid (m._{templateName} + m._{instantTemplateID} + m._{instantID}) \neq (n._{templateName} + n._{instanceTemplateID} + n._{instanceID}) \Leftrightarrow m \neq n,\ n \in MB_{IM}\}$$

Primitive Model: In a model base, a primitive model is a model that can not be decomposed. It has no knowledge about any relationship with other models. A primitive model can be specialized into one of a finite number of primitive models (specialization models). These specialization models differ in terms of their behaviors. The relationship between a model and its specialized models is *is-a*. In a system, the set of all of the primitive models is referred to as the *primitive model base* (PMB). In a PMB, a model cannot be decomposed.

$$PMB = \{m \mid \forall D(m) = \emptyset,\ m \in MB\}$$

Composite Model: A composite model in a model base is a model that can be decomposed into a finite number of composite models or primitive models or a combination that includes composite and primitive models. A composite model has knowledge of its internal structure (what components it has, how these components are connected to each other, and how these components are connected to the composite model itself). Relationships between the components and relationships between the part and whole is called *coupling*. The relationship between a composite model and its components is *has-a*. In a system, the set of all the composite models is referred to the *composite model base* (CMB). In a CMB, every model has a unique decomposition.

$$CMB = \{m \mid \forall D(m) \neq \emptyset, m \in MB \}$$

There are axioms listed in the following:

Uniformity: Any two models with the same name have identical structures (or isomorphic sub-trees).

$$\forall m, n \in MB$$

$$m_{.name} = n_{.name} \Leftrightarrow ((m_{.structure} = n_{.structure}) \vee (D(m) \cong D(n))$$

Scope: A model (primitive model, composite model) has no knowledge about the relationship outside of its boundary. For example, a primitive model has knowledge about its own state and functions but it has no idea of its relationship to other models.

Decomposition D(m): A composite model can be decomposed into a set of components and the coupling relationships among the components, as well as the coupling relationships between the components and the composite model.

Typing: A primitive model may be used as a basic element of a composite model. In a composite model, the siblings (the components in the same decomposition level) can be of different types (primitive or composite). A composite model can be a component of another composite model. This can be shown by the definition of primitive and composite models.

$$\forall\ m \in PMB,\ \forall\ D(m) = Ø$$

$$\forall\ m \in CMB,\ \forall\ D(m) \neq Ø$$

Strict Hierarchy: No model can appear more than once down any path of the model hierarchy tree.

$$\forall\ m \in MB,\ m \in D(m),$$

$$m \notin D(D(m))$$

Specialization: A specialization model inherits the ports interface and structure of its generalization parent, which is called a specialized model. The difference between the specialization models that inherit from the same specialized model is the behaviors. Only atomic models can be specialized.

Model Coupling: In SESM, model coupling presents the relationship between two models and the direct interaction between two individual models can be realized with a coupling. In a layered structure modeling approach, the model coupling represents the relationship between two ports from two models. We can say "model *A* couples with model *B*" (which is not precise) or "model *A*'s output port is coupled into model *B*'s input port." That means that the entities involved in a coupling relationship can be ports or

models. In SESM, when a model couples with another, it means at least one of its ports is coupled with the other model's port.

There are two types of couplings: *internal coupling* (C_i) and *external coupling* (C_e). *Internal coupling* connects two siblings in the same hierarchy level. It starts from one output port of one model and ends at the input port of another model. *External coupling* connects a composite model and its component. It starts from the composite model's input port and ends at the component model's input port. Alternatively, it starts from component's output port and ends at composite model's output port. A model can not have a model coupling between its own ports. For two models that are coupled, the coupling can be bidirectional and the cardinality is "many to many." For two ports that are coupled, the cardinality of the coupling relationship is "one-to-one".

4.2.2 Constraints in Distributed Computing Modeling

DOC provides the separation between software and hardware. The DOC abstract model has a set of well-defined constraints for specifying hybrid software and hardware models. These modeling constraints must be realized in SESM/DOC and may be presented by the following notations.

Software/Hardware Separation: In a distributed computing system, software components and hardware components need to be separated. The software components share the same structure (member data and member functions based on object-oriented model abstraction). The functionality of the software application components may be different. They are required to be executed on hardware components. Software

components can be changed without affecting the hardware components. Hardware components provide the resources for software execution. Alternatively, the hardware components can be independent. Both software and hardware are separated from each other so that their models can be defined individually.

Software Interaction: There is no direct interaction between two software components. The interaction between software components is indirect. All software interactions have to go through the one or more hardware components.

Software/Hardware Mapping Direction: There is a mapping relationship between software components and hardware components. This mapping is unidirectional: from software to hardware. The mapping assigns software components to hardware components.

Software/Hardware Mapping Cardinality: The cardinality of software and hardware mapping is many-to-one. Multiple software components can be mapped onto one hardware component. A software component can only be mapped into one hardware component.

4.2.3 Layered Structure Decomposition for Distributed Computing Systems

As we have seen above, in order to design logically correct distributed computing models we must introduce the DOC abstract model into SESM. The above constraints need to be defined in terms of SESM models.

First, SESM has no facilities adequate for presenting the separation between software and hardware model components. The concepts of composite model,

decomposition (D(m)), and specialization (S(m)) provide *has-a* and *is-a* relationships for system components. The relationship between software and hardware is conceptually different than decomposition and specialization relationships. Software running on hardware has neither the *is-a* nor the *has-a* relationship with the hardware and, similarly, hardware running a software program has neither an *is-a* or a *has-a* relationship with the software. The coupling relationship defined in SESM needs to be extended for modeling software to hardware assignments. In SESM, model coupling presents the information transportation between models by defining the unidirectional coupling between ports. This coupling relationship must be extended to describe the relationship between software and hardware components. The coupling relationship does not have the *Software Interaction, Software/Hardware Mapping Direction,* and *Software/Hardware Mapping Cardinality* modeling constraints. In distributed computing systems, the relationship between software and hardware components is not as simple as the *has-a* relationship of a composite models and so *external coupling* is not sufficient. Also, there is no simple composite relation between the software and hardware components. The relationship between software components and hardware components is very important in a distributed computing system. To handle it, a new specification must be defined in SESM/DOC.

Second, the visual model description in SESM cannot be used to separate software and hardware models. The SESM visual modeling cannot describe the relationship between software components and hardware components. The SESM visual does not provide the separation for DCO, LCN and OSM in a network system. In a

network system, software components need the resources in hardware components to execute and communicate with each other. These resources include such things as CPU calculation capability, memory storage, routing facility, and communication bandwidth. That means a software model has many interactions with its corresponding hardware. When the scale of the system grows we have to face the problem of reducing the couplings. A separate view of the interactions between software and hardware is needed.

Third, the database has no facility to distinguish the difference between software and hardware. This is related to our first and second points. Once we can separate the software and hardware and can present their interactions in SESM, we can add new abstractions in the database to distinguish the difference between software and hardware and also store their relationships.

Based on our discussion above, to present the abstraction of the separation of software and hardware in a distributed computing system, we combine the DOC mechanism into SESM. This brings layered structure and layer mapping concepts into SESM (as shown Figure 25), which will realize the modeling constraints in distributed object computing.

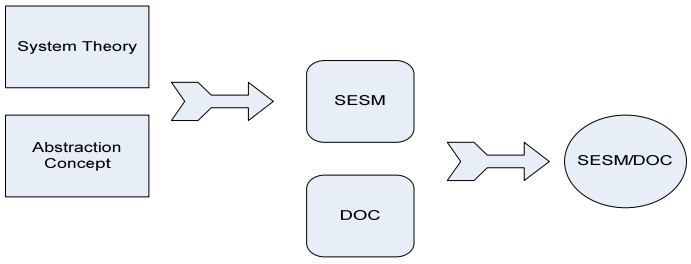


Figure 25. Conceptual Approach for SESM/DOC

The following are the basic concepts that are defined for the layered structure decomposition.

Notations:

Model Layer – ML

Mapping – $M(ML_s, ML_h)$

ML_s–$m_{software;}$

ML_h – $m_{hardware;}$

Definitions:

Model Layer (ML): In the co-design modeling approach, the software components and hardware components belong to the *software layer (ML_s)* and the *hardware layer (ML_h)*. A model layer is defined as a group of models that share the same or similar structural and behavioral properties. The models in the software layer have similar structure and behavioral properties in that they all are in the computation domain and they all have methods, tasks, and arcs (Butler, 1995). Each software component uses the same means to communicate with the hardware components. Also all of them have to load themselves into hardware. The hardware models in the hardware layer have connections among themselves. They are all physical devices and have bandwidth and computing and transportation capability. The models in one layer have a uniform way to interact with the models in aother layer.

A model layer is different from a composite model. It has additional constraints than a composite model. Models in a composite model do not need to share the same structural or behavior properties. Component of a composite model can have coupling

relationships. A composite model allows its components to interact with models not in the composite model. We have the following relationship for modeling the constraints among the SESM/DOC models.

$ML_s \subset MB$, $ML_h \subset MB$,

$\forall m \in ML_s, m \notin ML_h$

$\forall n \in ML_h, n \notin ML_s$

Axiom:

Model Mapping: The concept of a *model layer* helps to separate the software models and hardware models. So, instead of studying the interaction between individual models in the software and hardware layers, emphasis is given to the interaction between the layers. We call the relationship between layers *mapping*.

In co-design modeling, mapping is considered to be distinct from coupling**.** Coupling entails information transportation between two models. In mapping, the software component consumes the resources of a hardware component (e.g., CPU computation power and memory). So, mapping is defined as an assignment relationship. It is unidirectional. Mapping has more constraints than coupling. The mapping between layers is unidirectional (from software layer to hardware layer). The cardinality of mapping is "many to one" (that is, multiple software components can map to one hardware component). Model mapping connects two model layers. For example, the communication between two software models needs to go through the hardware layer by system mapping. In the same layer, there may also exist direct interaction between models, such as the coupling between two hardware models in a hardware layer. As both

individual models and ports can be the basic elements involved in model coupling, model layers, individual models, and ports are needed as the basic elements to define mapping. The model-layer mapping is realized by the mapping between individual models belonging to different layers.

$m_i \in ML_s$, $n_j \in ML_h$,

$M(ML_s, ML_h) = \{M(m_1, n_1), ..., M(m_i, n_j)\}$

$$M(m,n) = \{ C_1(m_{portOut_1}, n_{portIn_1}), C_2(m_{portOut_2}, n_{portIn_2}), \ldots, C_i(m_{portOut_i}, n_{portIn_j}) \}$$

Here, *i* and *j* are the number of the models involved in the mapping between the software and hardware layers respectively.

Figure 26 shows the difference between model coupling and model mapping. Model coupling presents the relationships between "ports". Internal coupling shows the information flow from one model's output port to another model's input port. External coupling shows the information flow from either one model's input port to another model's input port or one model's output port to another model's output port. Model coupling describes the relationship between ports. When the concern is only for the relationship between two models, coupling can be used to represent the general connection between two models. For model mapping, it is the representation of the assignment from one model layer to another model layer. The definitions and axioms introduced in this chapter will be used in developing the SESM/DOC modeling approach.

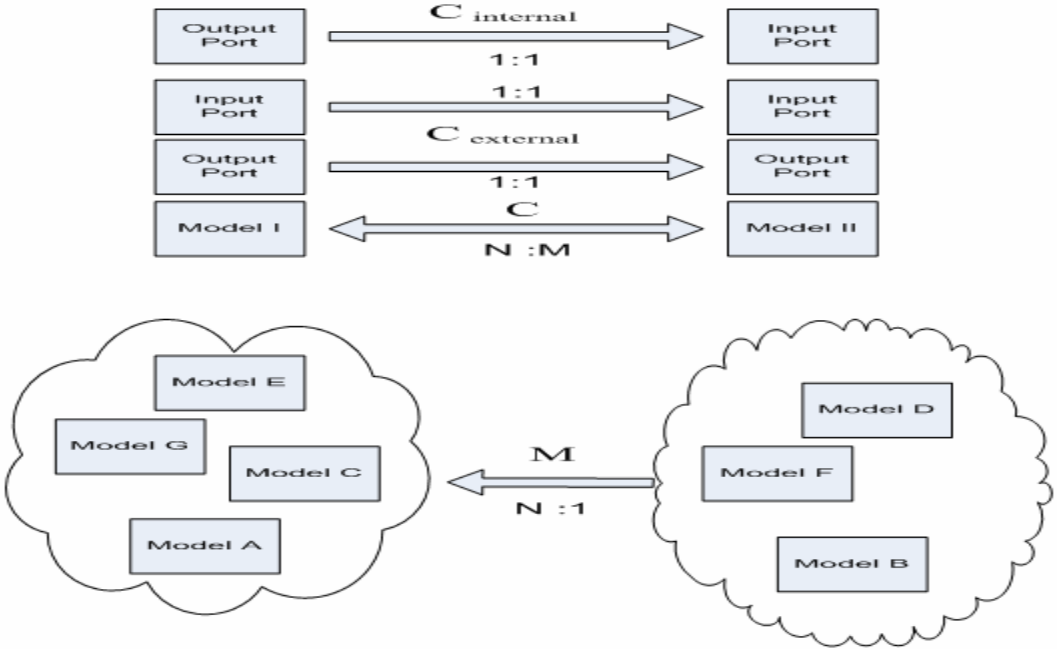


Figure 26. Model Coupling and Model Mapping

4.3 Model Bases for Layered Structure Modeling

In SESM, there are three model bases for a designed model (MB_{TM}, MB_{ITM}, MB_{IM}). These model bases separate models based on whether the model is a template model, an instance template model or an instance model. In a co-design system, putting all of the models that belong to different model layers into the model bases is not an appropriate co-design. This section defines model bases that account for the above requirements.

Modularity is an important feature in layered structure system modeling. It provides clear boundaries to different layers. In SESM/DOC, we define multiple model bases for distributed object computing system modeling. Inherent with SESM, SESM/DOC has the facilities to create a Template Model (TM), an Instance Template

Model (ITM), and a Model Instance (MI). Inherent with DOC, the three layers specified in DOC are supported by SESM/DOC.

Software layer (SESM/DCO): alternative software design models are supported using a predefined software model with constraints on its execution on specific hardware components.

Hardware layer (SESM/LCN): alternative hardware design models are supported using a predefined collection of hardware model components that comply with constraints that dictate which model components may be connected to one another.

Object System Mapping (SESM/OSM): alternative co-design models are supported under a set of constraints that dictate legitimate software to hardware mappings

Each of these has its own model types and model constraints. For the multiple model bases of a distributed object computing system, the first level of multiple model bases will be the software model base (SMB), the hardware model base (HMB), and the object system mapping model base (OMB). In each of the above model bases, there are three sub-models according to the separated layers – the template model, the instance template model and the instance model. So, for software models, there are the software template model base (SMB_{TM}), the software instance template model base (SMB_{ITM}), and the software instance model base (SMB_{IM}). In total, nine model bases are defined to support distributed co-design modeling, as shown in Table 11.

Table 11

Multiple Model Bases for Distributed Object Computing System

	Software Model	Hardware Model	Object Mapping
Template Model	SMB_{TM}	HMB_{TM}	OMB_{TM}
Instance Template Model	SMB_{ITM}	HMB_{ITM}	OMB_{ITM}
Instance Model	SMB_{IM}	HMB_{IM}	OMB_{IM}

4.3.1 Model Types for Co-design

As discussed in Chapter 3, a distributed object computing system has its own elements. When we combine SESM and DOC, these DOC elements should be classified into SESM model bases. To handle large-scale and complex systems, a "Group Model" concept is defined as a composite model which contains the same types of models. We introduce the model types based on their model bases.

Hardware Layer Model Types

According to DEVS/DOC specification, SESM/DOC supports the following hardware models:

1. Hardware Layer Model (HLM);
2. Processor (which includes CPU, Routing Unit, Transport Unit) Model (PM);
3. Network Interface Model (NIM);
4. Link Model (LM);
5. Router Model (RM);
6. Processor Group Model (PGM);
7. Network Interface Group Model (NIGM);

8. Link Group Model (LGM);
9. Router Group Model (RGM);
10. Processor and Network Interface Model (PNM);
11. Processor and Network Interface Group Model (PNGM).

Software Layer Model Types

Software layer in DEVS/DOC specification has two model types:

1. Software Layer Model (SLM);
2. Software Application Model (SAM)

SLM is a composite model which is composed from one or more SAMs. Each SAM is a primitive model which represents the abstraction of a software application which can run on an appropriate hardware component.

Object System Mapping Model Types

Unlike the software layer and hardware layers, the OSM layer is not a physical layer. It represents the abstraction of mapping from the software layer to the hardware layer in DEVS/DOC. It supports three model types: SLM, HLM and the system model. The first two model types are defined in previous chapters. The last one is a SESM composite model with certain constraints. For example, the mapping direction can only go from the software layer to the hardware layer.

Beside the above model types, modelers can define their own model types based on the system that is to be modeled. These user-defined model types should work together with the pre-defined model types.

4.3.2 Network System Model Constraints

It is important for a modeling approach and its realization to define constraints on composite model specifications. For example, a model may not contain other models as components or only certain types of models may be connected. DOC, as a layered distributed system design specification, brings co-design modeling constraints to SESM. In DOC's layered structure, we have a set of model types for describing software and hardware aspects of a distributed network system as described above. These model types are abstractions of particular entities, such as software application or router. Their structures and behaviors are defined according to the DOC and DEVS specifications.

To support co-design model specification, the SESM framework is extended to support the DOC model typing and constraints. The model typing in SESM/DOC entails three sets of model constraints. One is the composition relationship between two models that answers the question of which model can contain or be contained by which other kinds of models. The second set is the coupling relationship between two models that answers the question of which two model types can be connected (coupled). These constraints guarantee the right relationship between different DOC models according to the predefined model types. The third set is the mapping relationship between two model layers that answers the question about model assignment for co-design.

Hardware Layer Model Constraints

SESM/DOC supports the following composition constraints.

1. HLM can contain only group models (PGM, NIGM, LGM, RGM);
2. PGM can contain only PM;
3. NIGM can contain only NIM;
4. LGM can contain only LM;
5. RGM can contain only RM;
6. PNGM can contain only PNM;
7. PNM can contain only one PM and one NIM;
8. RM, NIM, LM, RM are primitive models

These model types and the connections between them will present different network topologies. In SESM, the connections are represented by couplings. The connection constraints between different model types are implemented by model coupling constraints as follows:

1. HLM can be coupled only with group models
2. PM can be coupled only with PGM;
3. NIM can be coupled only with NIGM;
4. LM can be coupled only with LGM;
5. RM can be coupled only with RGM;

6. RGM can be coupled only with RM and NIGM;
7. NIGM can be coupled only with NIM, RGM, LGM, PM, PNGM and RGM;
8. LGM can be coupled only with NIGM;
9. RGM can be coupled only with NIGM.

Software Layer Model Constraints

SESM/DOC supports the following model composition constraints in software layer:

1. SLM can only contain SAM;
2. SLM has to contain at least one SAM;
3. SAM is a primitive model.

SESM/DOC also supports the following model coupling constraints in the software layer:

1. SLM can only be coupled with SAM
2. SAM can only be coupled with SLM

Object System Mapping Model Constraints

The composite constraint in the OSM states that the system model contains and only contains one SLM and one HLM. The mapping constraint in OSM states that the only mapping in the system model is the mapping from SLM to HLM.

With SESM/DOC, modelers are given the flexibility to define their own models. Modelers can define new models for computer network applications such as the search engine network described earlier in this chapter. Even for distributed object computing co-design, they can still redefine the model components and create different groupings. For example, in the above hardware models we have a processor model (PM) and a network interface card model (NIC). These two models can be combined as a *processorNIC* model. This assumes each processor has one network interface card to connect to the network. Accordingly, the hardware constraints need to be adopted to match the hardware layer model types.

4.4 Summary

In this chapter, a component-based layered structure modeling approach is presented for co-design modeling of distributed network systems. Model layer and model mapping concepts are defined to specify the separation and synthesis of software and hardware components for the co-design modeling. Based on the DOC abstract model, a set of new model types are defined for the software and hardware parts of a distributed system. The group model concept is defined to help organize the same type of models. Based on these model types, a set of model constraints are specified to guarantee the correctness of the structure of the co-design network models. Multiple model bases are defined to support different model resolutions appropriate for software/hardware co-design system modeling.

Compared to the other modeling approaches discussed in Chapters 2 and 3, the layered structure modeling approach provides a well-defined specification for the separation and synthesis of the software and the hardware model components. This specification gives the software models and the hardware models distinct boundaries, so that they can be separately defined, developed, and synthesized. The software and hardware co-design provides a set of well-defined model components and relationships to specify distributed computer network systems.

This specification is based on co-design modeling concepts and model types. The logical layered structure modeling approach presented here provides the basis for developing the visual and persistent modeling capabilities described in Chapter 5.

5 CO-DESIGN VISUAL AND PERSISTENT MODELS PRESENTATION FOR NETWORK SYSTEMS

Visual modeling is an intuitive way for modelers to specify logical models. Visual modeling languages can enforce syntax and semantics of modeling formalisms such as DEVS/DOC (Burmester, Giese, & Henkler, 2005; Harel, 1987; Object Management Group, 2007; Sarjoughian, 2001). It is also good for the people who do not want to go to the code level to design models. Persistent modeling is a modeling approach that uses a database for model repository. It affords large-scale model management and helps with the model reusability and model structural complexity measurement. Co-design model representation and repository are very important in separating the design and repository of the software layer and the hardware layer in network system. Current modeling approaches do not visually separate the design of the software and hardware models for a network system and do not store/manage the co-design models in a database as supported in SESM. In this chapter, the approach for the co-design modeling visual representation and repository for network systems will be presented.

5.1 Visual Modeling

The co-design visual modeling needs to represent two kinds of information: the model components and the relationships between the model components. To visually present the logical models defined in Chapter 4, the SESM visual modeling approach is extended to be used in SESM/DOC.

5.1.1 Model Components

Based on this discussion, we will use the visual modeling elements of SESM to represent the primitive and composite logical model components defined in Chapter 4. The block diagram in SESM can be used both in primitive and coupled models, as shown in Figure 27. In Figure 27, there are three models, two primitive "*Router*" models, and one composite "*RouterGroup*" model.

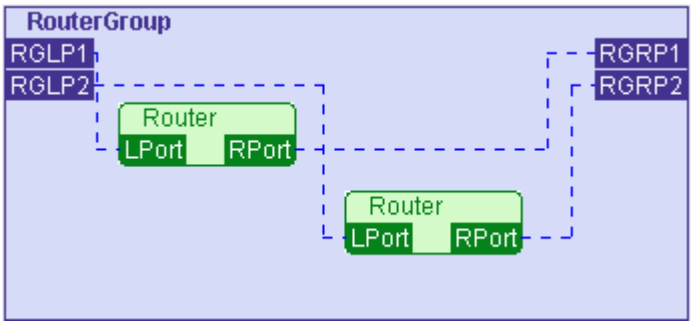


Figure 27. Block Diagram Visual Model

For large-scale and complex distributed object computing systems, the number of system entities can be large. For example, in a distributed network system, there may be hundreds of processors and hundreds of routers. To present all of these models one by one is impractical given the limitations of visual space on the computer screen. In SESM/DOC, it is important to visually create a group model to group the same kind of models, such as the "*LinkGroup01*" shown in Figure 28, which groups five "*Link01"* models. This helps to organize the models with the same model type.

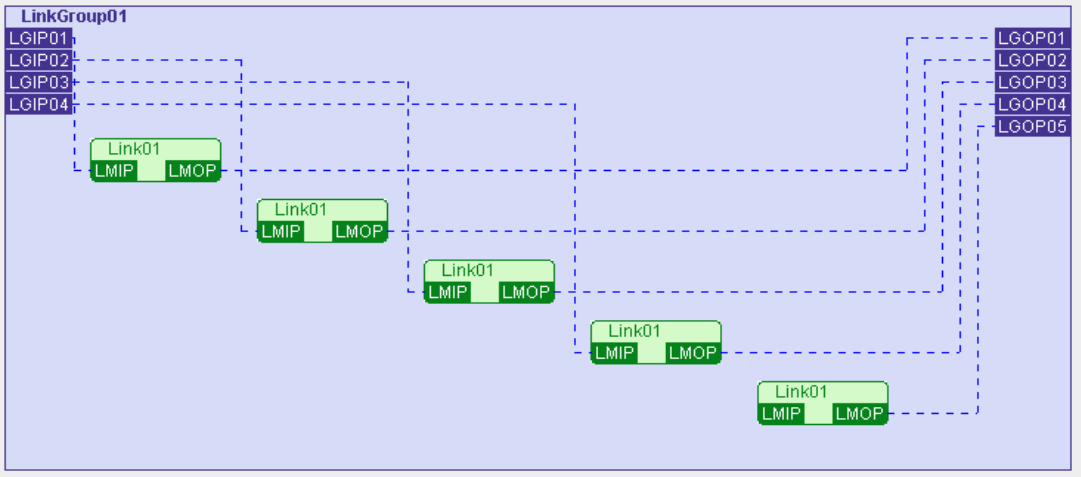


Figure 28. Link Group Model

5.1.2 Model Relationship

In both SESM and DEVS/DOC, the relationship between two models is presented by coupling. In SESM, the coupling in SESM is a dashed line with an arrow pointing to the direction of the information. For complicated systems, there are usually more connections between models and this could require many couplings. As described in Chapter 3, visual representation of a large number of couplings in a composite model can be difficult to view. It is important to organize the model couplings so that the model view is clear in a limited visual space. In SESM/DOC the approaches to reduce the number of couplings uses the concepts of the integrated port and bidirectional connection.

A model can have many ports which can lead to many couplings to other models. In SESM/DOC, the coupling relationship is based on the logical model presented in Chapter 4, so one integrated port can be created to identify which model is involved in the coupling relationship. In SESM and DEVS, the coupling relationship is tightly related

to the model ports. For internal coupling, the coupling has to be from one output port to one input port. For external coupling, the coupling has to be either from one input port to another input port or one output port to another output port. To show the connection relationship between models using the non-arrowed segmented line, we do not need to know the about the input or output ports. The only thing we need to know is from/to which model we are connecting. So in SESM/DOC, a model only needs to have one kind of port, the identity port which integrates at least one component port to be used for the model connection. This port is defined as an integrated port. This integrated port integrates all of the ports of the model (Xie, 2004). For the integrated port, the arrowed dashed line in SESM is not sufficient to present the information flow, so in SESM/DOC, a bidirectional information flow is presented using a non-arrow dashed line.

In order to make the visual model easy to read for a primitive model, we design two integrated ports: one on its left and one on its right. Each of them is both input port and output port. For a composite model, depending upon the components it has, it can have multiple ports which can be connected to its components and other models. The integrated port and bidirectional coupling approaches reduce the complexity in visual model design by reducing the number of couplings. The model connection tells which models are involved in a particular model connection, as shown Figure 29.

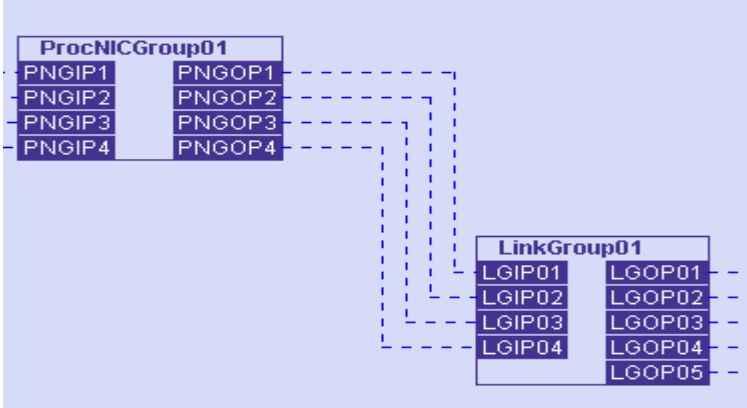


Figure 29. The Non-arrowed Segment Line for Model Connection

In Figure 30, two features of SESM/DOC are presented. The first one is the grouping model which is the composite model including multiple same type models. For example, *LinkGroup01* has five link models inside it. The second feature is the non-arrowed dashed line showing the connections. The connection among hardware in DOC gives the topology of the distributed network. The grouping model helps to organize the visual model deployment and helps to reduce the complexity. In the OSM model layer, the mapping relation has an arrow to show how a software model is mapped onto a hardware model through the identity port of a software layer and the integrated port of a hardware layer, as shown in Figure 30.

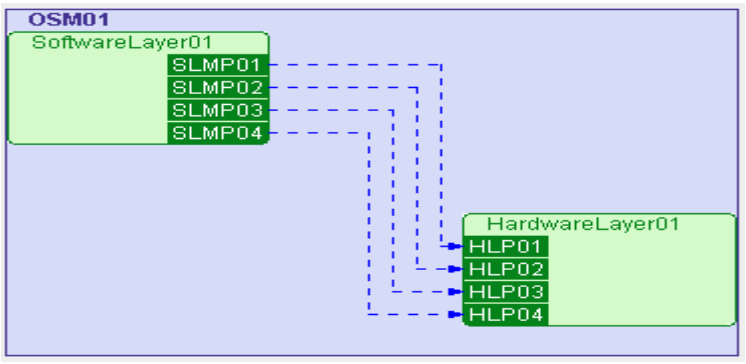


Figure 30. OSM Model

Every dashed arrowed line in the mapping relationship is not trivial. For example, the system in Figure 31 is a different from the system shown in Figure 30. There are two software applications (SoftwareApplication03 and SoftwareApplication04) running in the same processor (the first processor02 model in processor group) in Figure 31. That means the CPU and memory in the processor will be shared by two software applications. In Figure 30, however, each software application runs on its own processor. This visualization of model connections significantly reduces the complexity of the system model for a large-scale and complex system, and makes a graphical representation of the models simpler to view and manipulate. In next chapter we will show examples of visual models for the search engine network system.

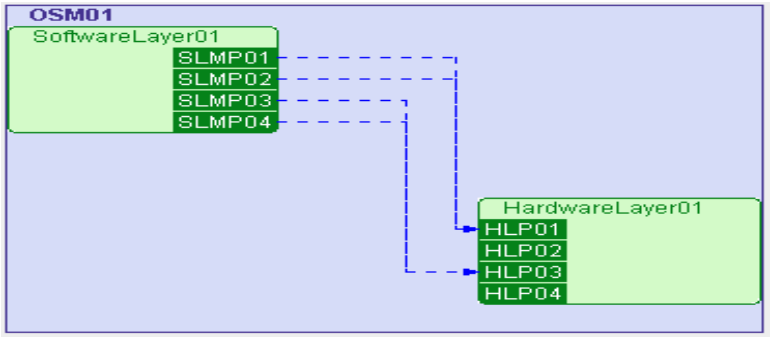


Figure 31. Alternative OSM Model

5.1.3 Tree Structure and Block Diagram Views

Besides the block diagram model we saw above, SESM/DOC also provides a tree structure view of models, as shown in Figure 32. In the tree structure view, every model in the mode base is a node. The primitive ones are the leaves of the tree. From the tree structure view, it is easy to tell the model relationships across multiple levels, while in a block diagram view, the composite model's component and their relationships can be

viewed. The information of the model specialization relationship is presented in both the tree structure and the block diagram. In the former, the letter “S” is used for identify specialized models. In the block diagram and the tree structure different colors are used to help identify models. In Figure 33 we can see the Processor02 model is specialized as a *singleCoreProcessor* and *doubleCoreProcessor* which are both *Processor02* but with different properties.

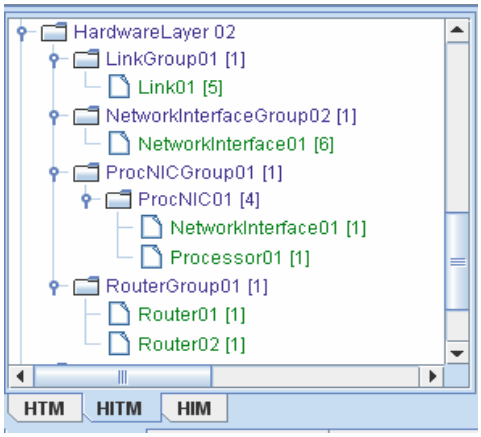


Figure 32. SESM Model Tree Structure

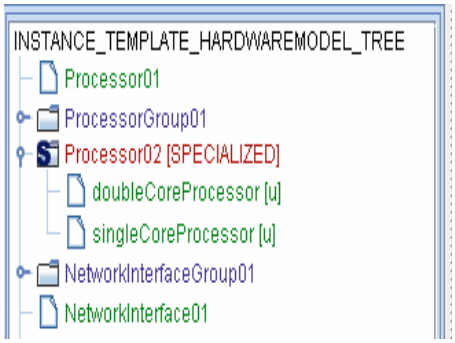


Figure 33. Model Specialization

5.1.4 Multiple Layer Model Representation

To support the DOC abstract model in SESM, separating the visual models for software and hardware layers is important. It is necessary to have distinct views of the layers. When a modeler is working in a software section, all of the model candidates in the current model tree are software models. This should also be true for hardware models. Based on the separation of the logical software and hardware model layers, SESM/DOC provides three working sections for the visual model representation: the software model working section, the hardware model working section, and the system model working section. The system modeler can switch among these three sections as needed. Each of the sections has a unique block diagram and model tree (the software, the hardware and the system tree structure), as shown in Figure 34.

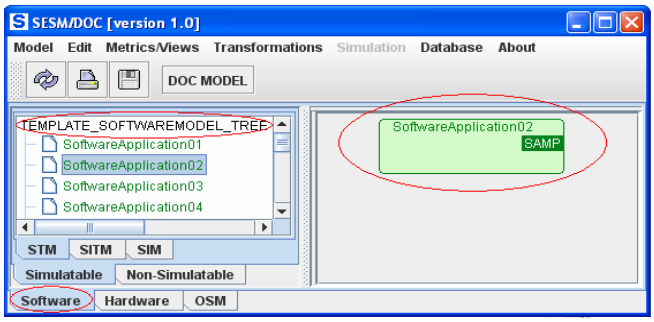


Figure 34. Multiple Sections for Visual Modeling

In Figure 34, the current section is for the software layer. All of the models created and edited in this section are software models. The modeler will not have access to hardware or system models. This ensures that the modeler will not mistakenly define software, hardware and system models.

5.2 Model Persistence

As described in Chapter 3, SESM stores all of the logical models in its database. This is a much better approach than the file system in DEVS/DOC where models are saves as individual files. From a modeler's perspective, it is difficult to see the relationship between models through a file system. According to the separation of the logical model and in order to provide the modularity and be consistent with the model constraints for system co-design discussed in Chapter 4, SESM/DOC provides three sets of database tables for software, hardware, and system models. This separation in the database systematically manages the DOC abstract model for both the logical and visual models.

Figures 35, 36, and 37 show database schema designs that are extended for DOC models (Elamvazhuthi, Sarjoughian, & Hu, 2007).

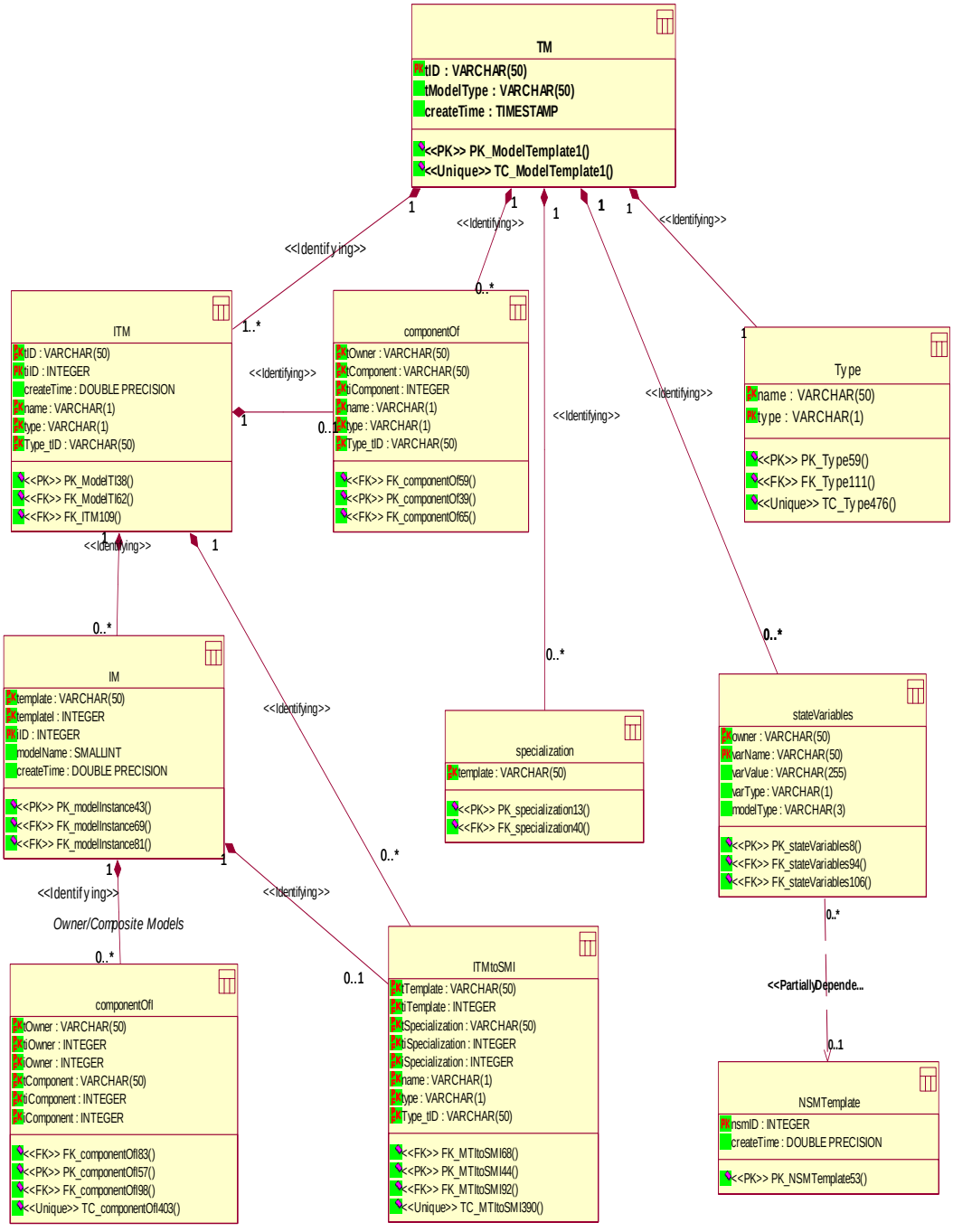


Figure 35. DOC Data Schema - Kernel

Figure 36. DOC Data Schema – Ports, Coupling, State Variable and Statistics

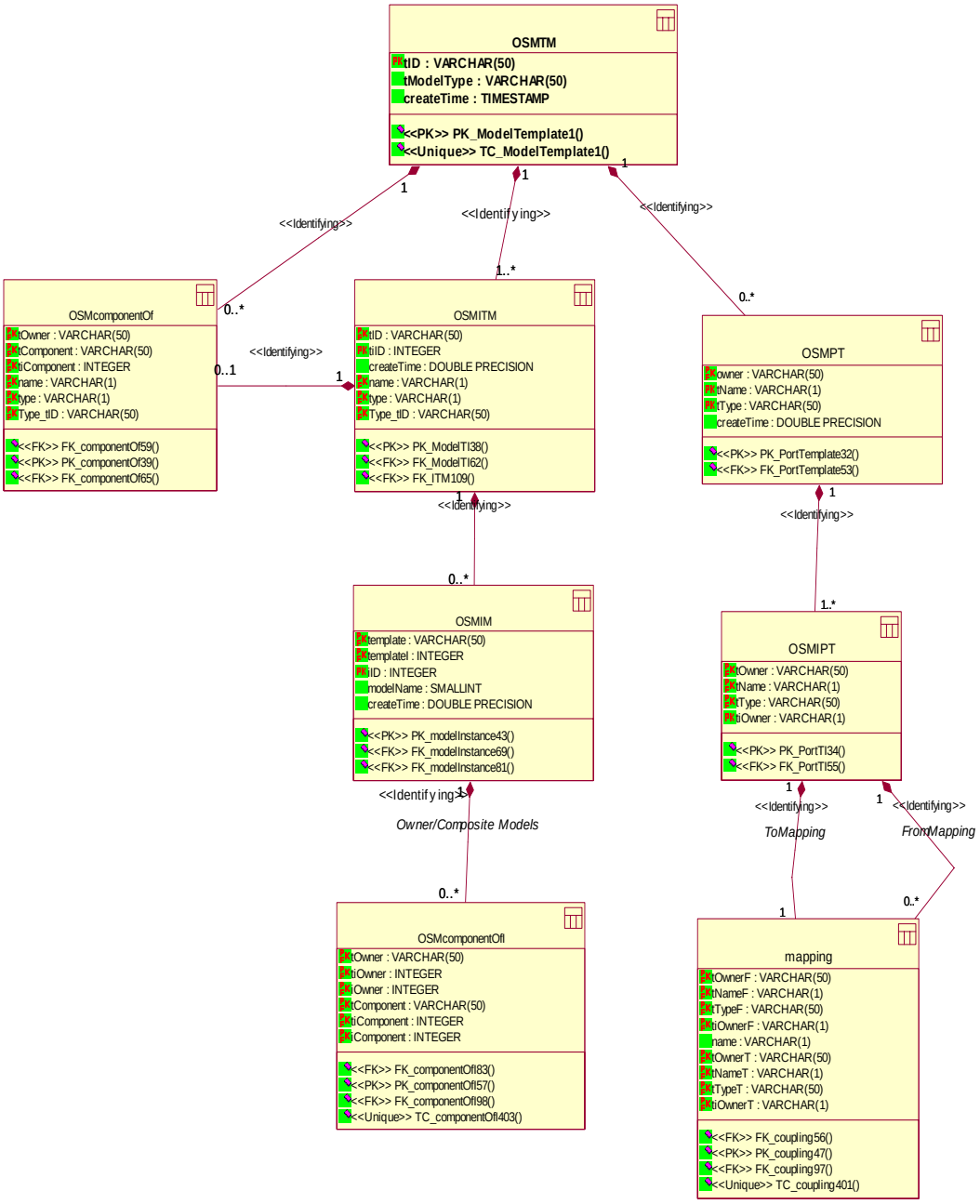


Figure 37. DOC Data Schema – OSM Model

Figure 35 shows the kernel data schema for software models and hardware models. In this figure, the “TM” stores the template models for software or hardware models. For example, the decomposition relationship for a composite model is stored in the table of “componentOf”. The “ITM” table has the records of the instance template model discussed in the Chapter 3. The “Type” table has the network systems co-design model typing information which enforces the network systems co-design modeling constraints. Every composition relationship and coupling relationship will be checked again this “Type” table to guarantee the correct model type is used. Figure 35 also shows the specialization information and the state variables are also stored in the data tables.

Figure 36 provides the data schema with the model ports, couplings and state variables. It also contains the structural complexity metrics for one of the software, hardware, or system models in the “Statistics” table which is in charge of the measurement of co-design system structural complexity based on quantity information such as the number of model components, the number of model ports, and the number of couplings.

The OSM data schema is similar to the software and hardware data schema but with some differences. As shown in Figure 37, the OSM data schema does not have a coupling table. It has a “mapping” table which stores alternative software models to hardware models assignments as shown in Table 12. The components of the OSM template model are the models chosen from the software and hardware layer.

Table 12

OSM Mapping Table

mapping							
OSMtOwnerF	OSMtiOwnerF	OSMtNameF	OSMtTypeF	OSMtOwnerT	OSMtiOwnerT	tNameT	tTypeT

The specifications of this mapping table is:

1. "mapping" table is the table for object system mapping model mapping
2. "OSMtOwnerF" is a foreign key referring to "OSMname" from OSMmodelTemplate. It is the name of the model from which the mapping starts.
3. "OSMtiOwnerF" is a foreign key referring to "OSMtiID" from OSMmodelTI.
4. "OSMtNameF" is a foreign key referring "name" from OSMportTemplate. It is the name of the port from which the mapping starts.
5. "OSMtTypeF" a foreign key referring to "OSMtType" from OSMportTemplate.
6. "OSMtOwnerT" is a foreign key referring to "OSMname" from OSMmodelTemplate. It is the name of the model at which the mapping ends.
7. "OSMtiOwnerT" is a foreign key referring to "OSMtiID" from OSMmodelTI.
8. "OSMtNameT" is a foreign key from referring to "OSMtName" from OSMportTemplate. It is the name of the port at which the mapping ends.
9. "OSMtTypeT" a foreign key referring to "OSMtType" from OSMportTemplate.

10. The primary key is a multiple-field primary key which includes “OSMtOwnerF”, “OSMtiOwnerF”, “OSMtNameF”, “OSMtTypeF”, “OSMtOwnerT”, “OSMtiOwnerT”, “OSMtNameT”, and “OSMtTypeT”.

Figures 35, 36, and 37 show that SESM/DOC almost triples the number of tables in SESM to separate the persistent models of the software, hardware, and object system. However, they are not mere duplications. Based on the SESM/DOC constraints we discussed above, the model typing issues play an important role in the database. In other words, the SESM/DOC database needs to guarantee the model typing correctness. Also, the separation of the DCO, LCN, and OSM models in different tables provides the modularity for persistent model manipulation. When the hardware schema is changed, the model data of the software model and the system model will not be affected.

In the SESM/DOC database, the DOC constraints are guaranteed by two typing tables: software type table and hardware type table, as shown in Tables 13 and 14. Each of the tables has two columns, one is for the model ID and the other is for the model types.

Table 13

Software Model Type Table

SWModelID	SWModelType
Text File Server	SOFTWARE
Two Servers Two Clients Software Layer	SWLAYER
…	…

Table 14

Hardware Model Type Table

HWModelID	HWModelType
Link	LINK
LinkGroup	GROUPLINK
"H" Style Hardware Layer	HWLAYER
…	…

These model types give the composition and connection constraints for distributed object computing systems discussed in Chapter 4. For example, the link group model (LGM) can only contain link models (LM). When we add a model component in LGM, the type of the container model and the content model are checked with the model type tables. If the added component is a link model (LM), then the SQL query to the database succeeds. Otherwise, it fails and an error message is returned. For example, if the modeler wants to add a router model (RM) into a link group model, there will be the "A Link Group Model Can Not Contain a Router Model!" error message.

Also, for the connection constraints check, SESM/DOC will check both models involved in a coupling relationship. For example, a router group model (RGM) can only be connected to a network interface card group model (NIGM). If a RGM is connected to a processor group model (PGM), the "A Router Group Model Can Not Be Connected To a Processor Group Model!" error message is generated. This enforcement of model typing and model constraints helps the modeler to use models that are consistent with the DOC abstract model.

Besides checking the composite and connection constraints, a model type is also important in object system mapping. In Chapter 6, when a system model is created, only one software layer model and one hardware layer model can be added as the system model's components. Furthermore, only a software layer model and a hardware layer model can be involved in a system mapping relationship. For example, if we try to map two hardware layer models, an error message will be generated.

The new database schema in SESM/DOC helps the modeler with model development and management. The separated database table sets provide the modularity for co-design persistent modeling because once software model or hardware model types or constraints change, they will not affect each other. Therefore, new model types can be added into the model type table. This helps SESM/DOC to be extended in future.

5.3 Summary

This chapter provides the visual and persistent modeling capabilities that are necessary for network system co-design. The visual modeling approach enables the visual separation and synthesis of different model layers defined in Chapter 4. The separate working sections are defined to help with the software/hardware visual model designs. To deal with the scalability and structural complexity of model visualization, the bidirectional model coupling, integrated port and group model concepts are developed. This approach reduces the complexity for large-scale network system modeling and reduces the difficulty modelers could experience when there are a large number of couplings. Database schemas are developed to separate the models in the software, the

hardware, and the system model layers. The mapping table in the OSM schema supports synthesis of the software and hardware models. The software model and hardware model type tables help ensure co-design modeling relationships are defined. The tables also support the obtainment of the structural complexity metrics for the software, hardware, and system models.

6 DISTRIBUTED CO-DESIGN MODELING EXAMPLE

In this Chapter, the distributed co-design modeling example of the search engine system mentioned in Chapter 4 will be used to show how the capabilities of the SESM/DOC modeling environment helps a modeler to develop a distributed network system.

6.1 The Search Engine Network System Problem

The co-design modeling approach developed in Chapters 4 and 5 is used for the search engine system described next. A search engine network is an interesting system to be modeled and simulated (see Figure 38). To analyze or design this search engine network system, one needs to consider the software applications, the network hardware, and how they can be synthesized. The details specific to the software, the hardware and the assignment of software on hardware determine important aspects of the system such as performance (i.e., percentage of successful data transmission). This requires the modeling of such system to separate the software parts and hardware parts.

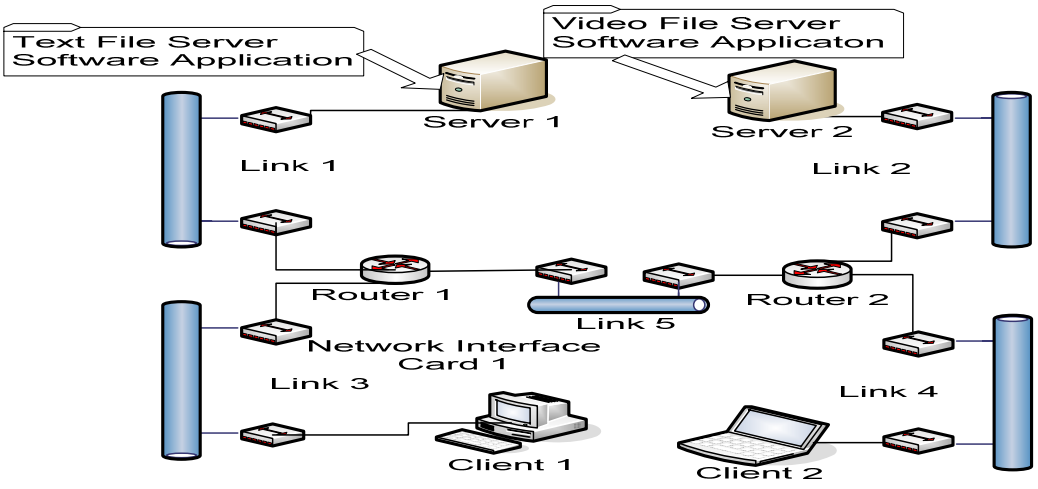


Figure 38. Search Engine Network System

A simplified search engine network system is shown in Figure 38. Because the topology of this network example looks like a letter “H”, it is called an “H” style network system. In Figure 38, there are search engine servers which provide the search results, clients who make search requests, and the network between the servers and clients. The servers and clients are composed of both software and hardware. The clients use some designated software to make the search requests. Then, these requests go through the links and arrive at servers through the network routers. Depending on different search keywords in the requests, the requests will be directed to specific servers which are in charge of handling different categories of search requests, including the particular search key word. For example, the request “African Mountain” will be directed to the server which is in charge of the index from “A” to “L”.

In order to narrow the search range and get the most related search results faster, the clients can add more key words, such as “African Mountain” plus “English”, meaning the search is about the English file for “African Mountain”. The software in the server handles the search requests. Different requests (classified by their keywords) received by the same server will be treated by different applications within the server. For example, the search of “African Mountain” plus “English” and “African Mountain” plus “Chinese” will be treated by different applications in the same server.

In Figure 38, there are there are two search engine servers that provide searching services. Here we choose Figure 38 as an example to develop the distributed co-design model in SESM/DOC. As discussed in Chapter 4, clients use their software to make the

search requests. In response to the different requests received, the server will provide different searching results.

Different server methods are used to provide different responses in order to narrow the search range and get the most related search results faster. In our example, one server is in charge of the video request and the other is in charge of the text request. Alternative hardware configuration and topology also change the network performance.

6.2 Model Design

Models are designed in different working sections in SESM/DOC. First, the hardware and software component models are defined. Then, the model relationship between the hardware and software models is given.

6.2.1 Primitive and Composite Components

For this search engine network system, we need to begin by classifying which parts of the system should be modeled as “software” and “hardware” components. The classification work can be done based on the DOC, LCN, and OSM layers defined in earlier chapters. As we discussed in Chapter 5, in SESM/DOC we provide some grouping models to help integrate the same type of models, which make the visual models simpler to view. For system model integration, we provided a “software layer model” and a “hardware layer model” which are the basic elements for the OSM model. Based on the DOC abstract model in Chapter 3 and the logical model in Chapter 4, we have the candidate models shown in Table 15.

Table 15

SESM/DOC Network Models

SESM/DOC		
Primitive Model	***Composite Model***	
	Group Model	***Layer Model***
Software Application	NA	Software Layer
Link	Link Group	Hardware Layer
Router	Router Group	
Network Interface Card	NIC Group	
Processor	Processor Group	
NA	NA	OSM Layer

These models in Table 15 are the model candidates in a distributed object computing system model design. In this chapter, we will design different search engine network models using alternative software models and hardware models. In order to illustrate how SESM/DOC supports distributed co-design, we will go step by step to define the set of models shown in Figure 38, and then develop some alternative models.

6.2.2 Hardware Model

As discussed in Chapter 5, SESM/DOC provides three working sections for distributed co-design. The hardware model development should be carried out in the hardware working section.

We begin by launching the SESM/DOC. We will enter into the hardware working section by clicking the “hardware” tab shown in the bottom left corner in Figure 39. SESM/DOC provides the “DOC MODEL” menu for each of the software, the hardware, and the system model working sections.

In the hardware working section, one can click “DOC MODEL”, and choose to create a predefined hardware template model. The hardware model types defined in Chapter 4 are shown as the model candidates. Once a model template is chosen, a name for this hardware template model must be entered. This name will be saved in the database as this model’s ID (the ID for the template model is the primary key in the template model table). Also, once a model type is chosen, the model type is stored so that this model has the appropriate model constraints defined for it (see Chapter 4). We choose to create a processor and give the name, “SearchProcessor”, as shown in Figure 39.

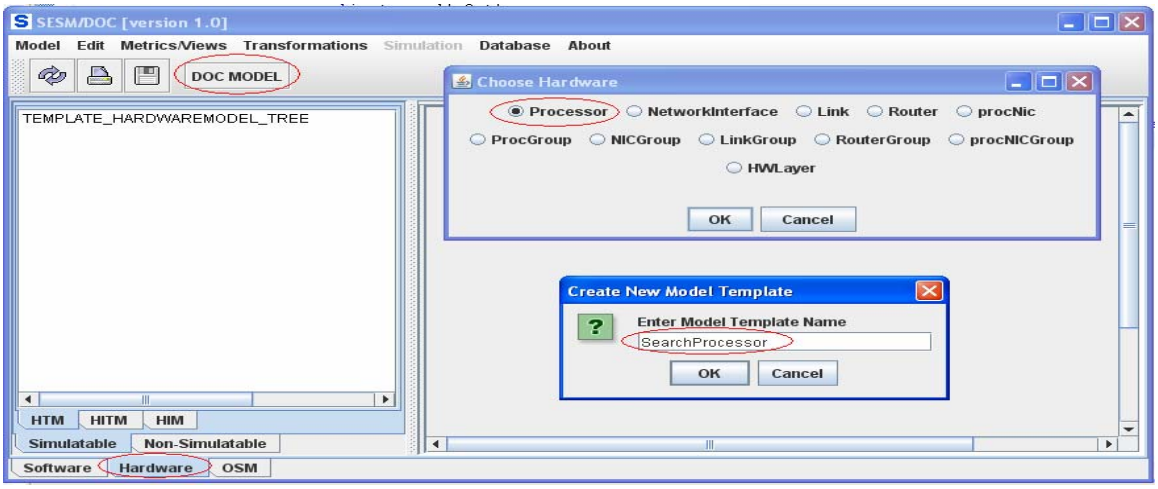


Figure 39. Primitive Hardware Model Development

For this processor model, we add integrated ports to it. For name convention, the group model ports are named as “xx*P?”. Here “xx” means the abbreviation of the group (for example, LinkGroup is LG). The symbol “*” indicates if the port is on the left or right in the visual graphic model. The symbol “?” represents the port number. “SPLP”

means “SearchProcessor Left Port”, and, “SPRP” means “SearchProcessor Right Port”. The ports can be added through the “add port” function in the “Edit” menu bar or through the tree structure and block views.

Composite models can be created based on the primitive models. We create a processor group model to combine all of the processors needed in the search engine network system model. Following the same steps of creating a primitive template model, we have a “ProcGroup” processor group model. Now one can add processor components into this processor group model from a drop down list, as shown in Figure 40.

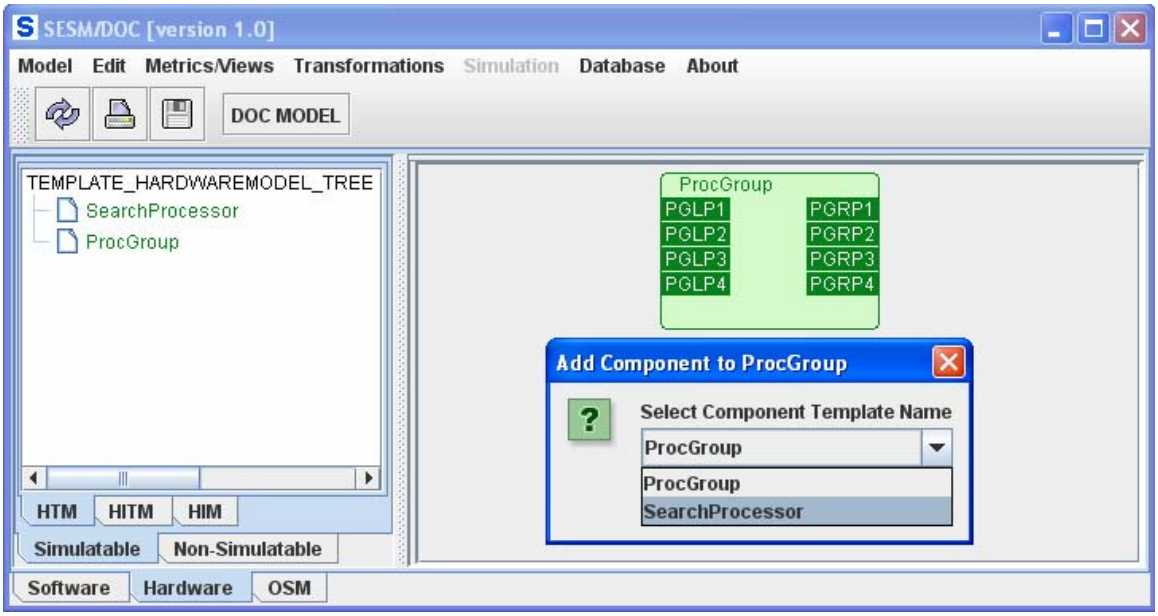


Figure 40. Adding Hardware Components into Hardware Group Model

When any component model is added, the model composite constraints discussed in Chapter 4 are checked to see whether this operation will violate any model composite constraints. According to the hardware model composite constraint “PGM can only contain PM”, there is no violation and the processor models can be successfully added as

components in processor group model. Otherwise, the add operation fails and an error message will be shown as “DOC Composite Constraint Violation: A PGM can only contain PM”.

We add four processors and specify the couplings among the processors and the processor group. As the hardware composite constraints are checked, the hardware coupling constraints are also checked to ensure the coupling relationship is correct. Otherwise, the coupling operation fails and an error message will be displayed. According to the hardware model coupling constraints in Chapter 4, the couplings between processors and processors and the processor group are correct. So, the complete processor group is created as shown in Figure 41.

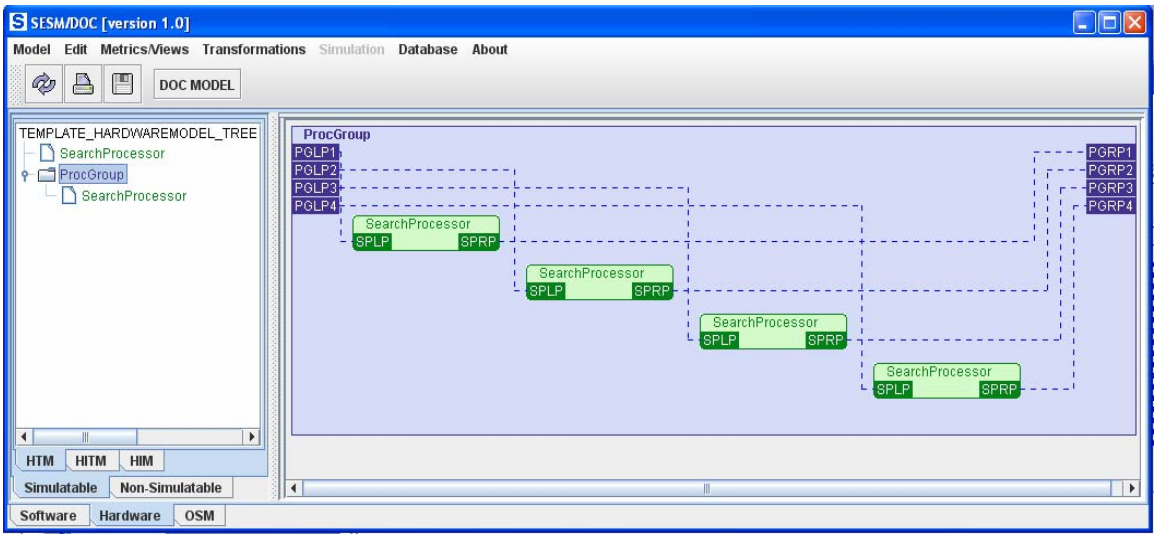


Figure 41. Hardware Group Model

In Figure 38, the network system uses both “star” and “bus” topologies. We name the hardware layer model after the “H” system, as shown in Figure 42. In Figure 42, we see all the group models and their coupling relationships. The group model defined in

Chapter 4 contains the same types of models. Figure 43 shows the instance template model tree structure. From Figure 43 we can see in the NIGM named “NICGroup”, there are 10 network interface cards and 3 specializations. The letter “u” after the specialized model name indicates that the model has not chosen which specialization will be used. These 10 network interface cards are in Figure 38. They are coupled with links, processors and routers to build up the search engine system shown in Figure 38. In fact, with the group modeling and model coupling approaches, SESM/DOC can design any topology for computer network systems. Using the integrated ports and bidirectional dashed lines, the model visual presentation is clear for a large number of models.

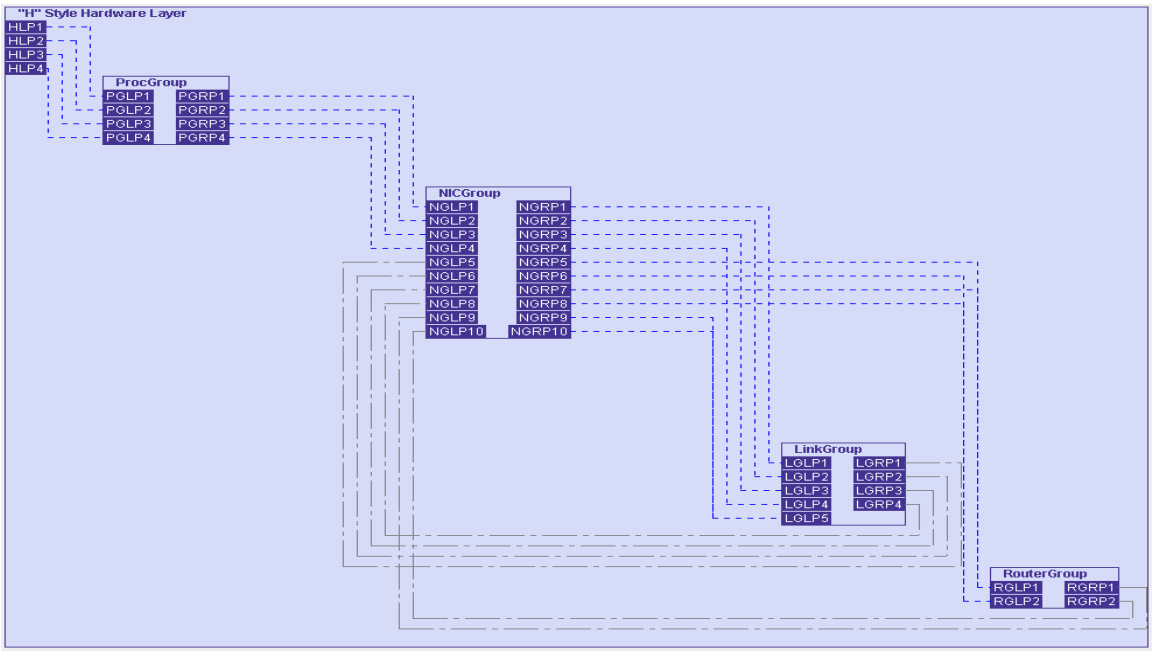


Figure 42. “H” Style Hardware Layer

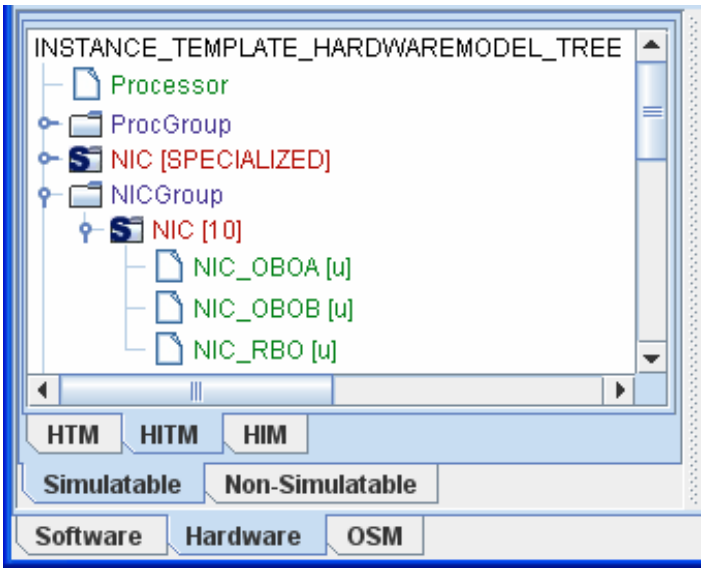


Figure 43. Instance Template Model Tree Structure for "H" Style Hardware Model

Figure 44 is an alternative hardware topology of the search engine network. Based on the shape of the network, as we did for "H" style network, we name this alternative one "I" style. This network has the same functionality as the one in Figure 38. The only difference is the network topology.

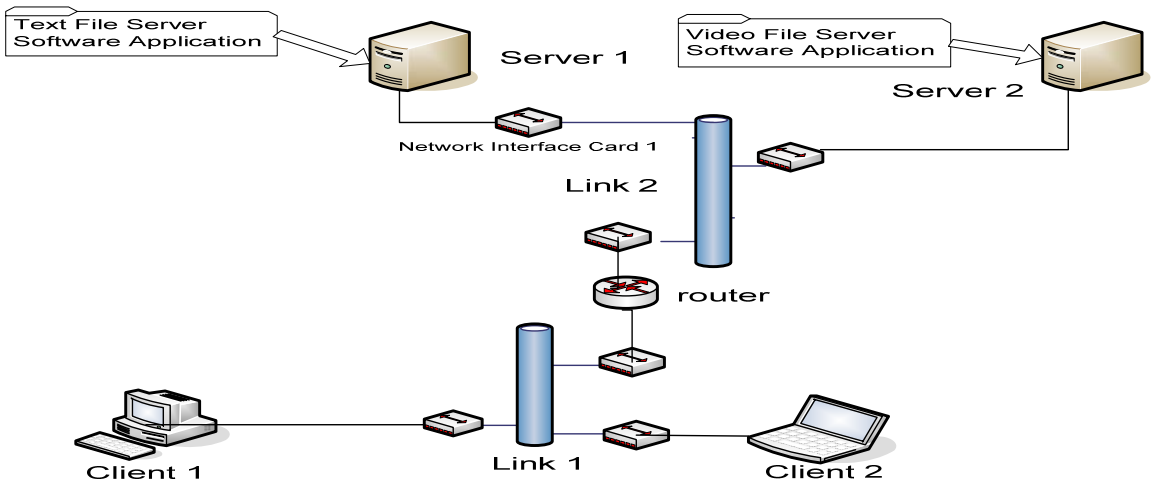


Figure 44. "I" Style Network System

The model of the “I” style hardware network is shown in Figure 45. This model has the *“I”NICGroup* model instead of the *NICGroup* model in the “H” style network. Also, the *“I”LinkGroup* replaces the *LinkGroup* model and the *“I”RouterGroup* replaces the *RouterGroup* model.

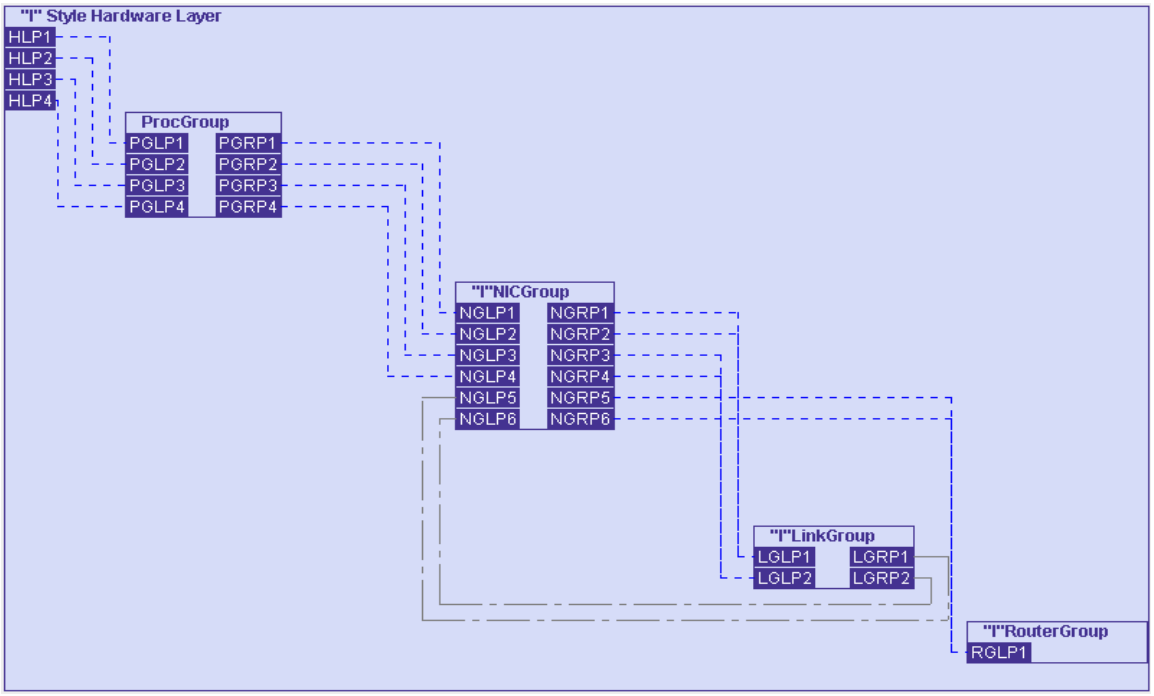
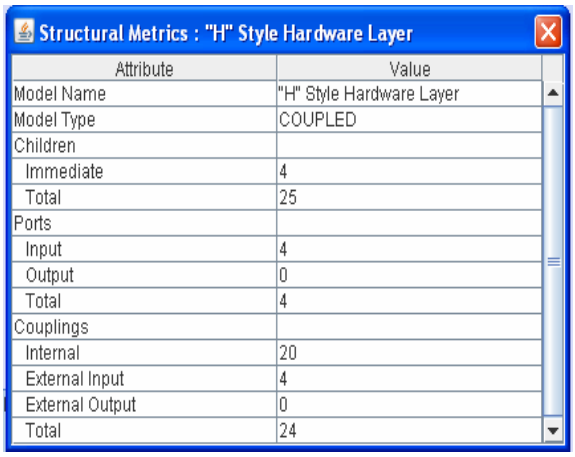


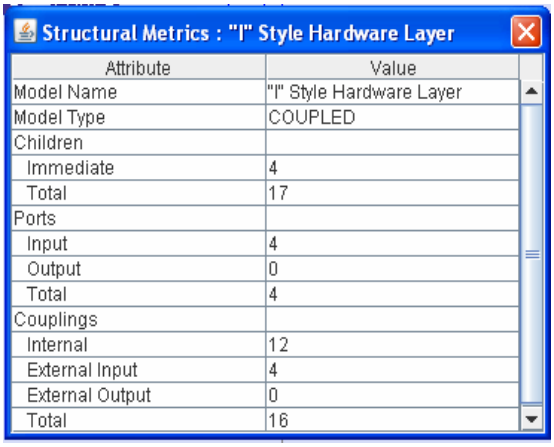
Figure 45. “I” Style Hardware Layer

For these two different networks, using SESM/DOC complex metrics, we can obtain an analysis to compare the two hardware models. Figure 46 shows the structural complexity metrics of “H” style hardware models and Figure 47 shows the structural complex metrics of “I” style hardware models.



Attribute	Value
Model Name	"H" Style Hardware Layer
Model Type	COUPLED
Children	
Immediate	4
Total	25
Ports	
Input	4
Output	0
Total	4
Couplings	
Internal	20
External Input	4
External Output	0
Total	24

Figure 46. Structural complexity Metrics for "H" Style System



Attribute	Value
Model Name	"I" Style Hardware Layer
Model Type	COUPLED
Children	
Immediate	4
Total	17
Ports	
Input	4
Output	0
Total	4
Couplings	
Internal	12
External Input	4
External Output	0
Total	16

Figure 47. Structural complex Metrics for "I" Style System

From the two metrics, we can see that complexity of the "I" style is smaller than the "H" style. For example, the total number of models in "I" style is 17 while the "H" style has 25. Furthermore, the "I" style has 16 total couplings while the "H" style has 24 couplings. We examine the performance differences of these two models after they are simulated.

SESM/DOC provides the model specialization facility. It is important for the models to share the same structural properties and yet have different behavioral properties. For example, as mentioned in Chapter 3, the network interface card (NIC) model is in charge of the network CSMA/CD (Carrier Sense Multiple Access with Collision Detection) protocols for the network model. The CSMA/CD protocol varies with different back off schemas: random back off schema (RBO), also called "Binary Exponential Back off Schema", one by one back off schema (OBOA), and one by one back off schema (OBOB). Based on the different back off schema, the NIC model can be specified with one of three specifications: NIC_RBO, NIC_OBOA and NIC_OBOB, as shown in Figure 48.

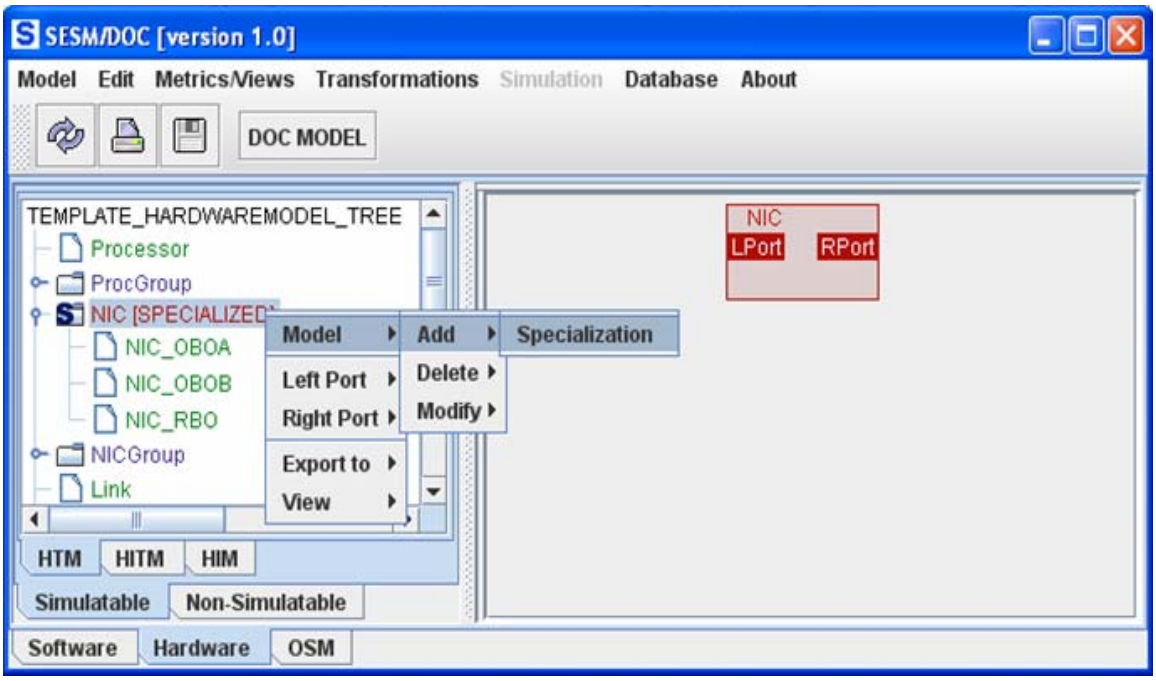


Figure 48. Hardware Specialization

To differentiate the specification for the network interface cards, we add the state variable “BackOffMode” into the NIC and give it different values. For example, for “NIC_OBOA”, we give the state variable “BackOffMode”, which is a string type, the value as “OBOA”, for “NIC_OBOB” we give “OBOB”, and for “NIC_RBO” we give “RBO”, as shown in Figure 49.

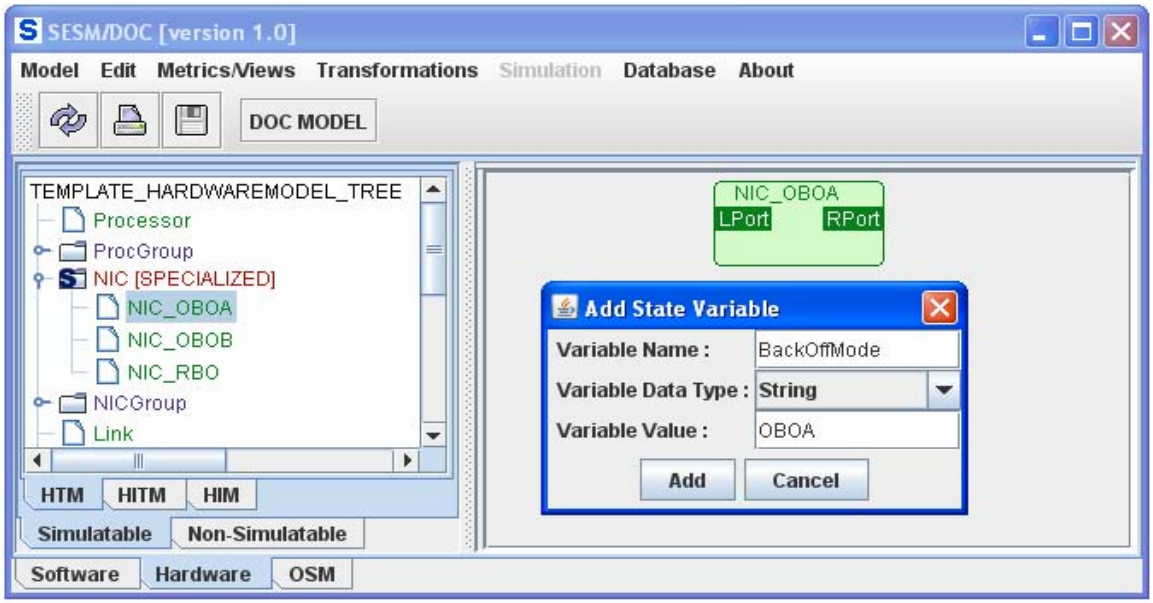


Figure 49. Adding State Variables for Hardware Specialization

6.2.3 Software Model

Similar to the hardware layer model specification, all software models can be specified using the model abstractions that are provided in the software working section. In Figure 38, there are four software models — two server applications and two client applications. We launch SESM/DOC and enter the software working section by clicking the “Software” tab in the bottom left. In the software working section, the choice of software in the DOC MODEL allows the creation of software models. Following a

similar process as the hardware model design, a software layer model named “Two Servers Two Clients Software Layer” is created. We also create software application models for the servers and clients shown in the Figure 38. As discussed in Chapter 3, the software model can have three working modes: *none, object*, and *method*. This working mode parameter determines the multi-thread level that the software object supports. The working mode is important for the server software application. So, for each server application, it can be specified as one of three specialized models which stand for the software objects with different working modes.

Now, the software application models can be added to the software layer model as shown in Figure 50. In the software model working section, all of the models that the modeler can access are the software models. So, when adding the software components into the software layer model, the listed candidate models are all software models.

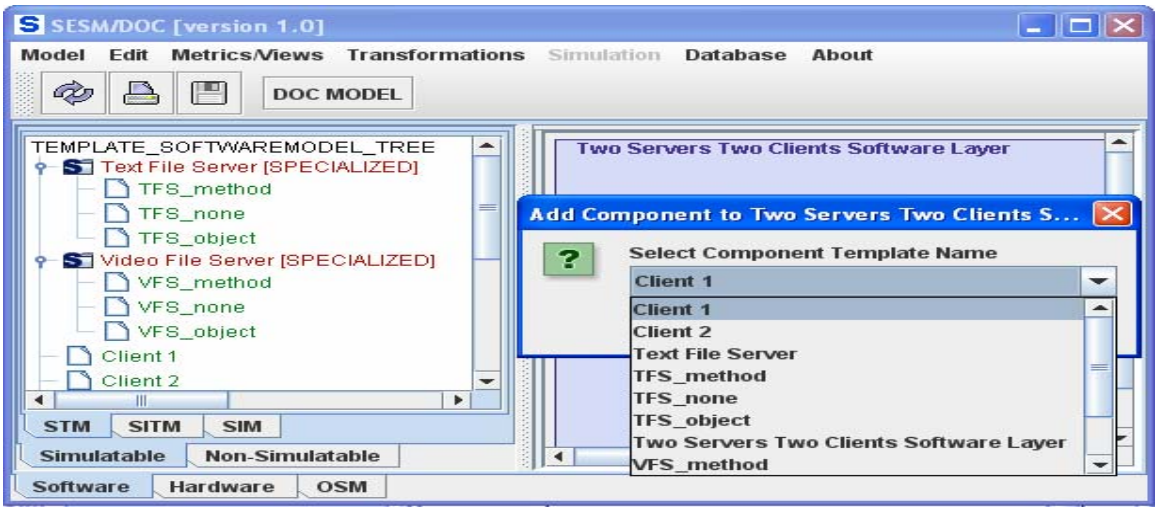


Figure 50. Adding Software Models into Software Layer Model

After the components are added into the software layer, based on what we discussed in Chapters 4 and 5, couplings between the software application components and software layer model can be separated, as shown in Figure 51. In this example, the "method" mode object is chosen for both "Text File Server" and "Video File Server" software applications.

Also, all of the software model composite and coupling constraints discussed in Chapter 4 are enforced to disallow logically incorrect composite models. The logically correct software layer model is shown in Figure 51. To differentiate the specification for the servers, we add the state variable "mode" into the server application and give it different values. For example, for "TFS_method", we give the state variable "mode" the value as "method", for "TFS_none" we give "none", and for "TFS_object" we give "object".

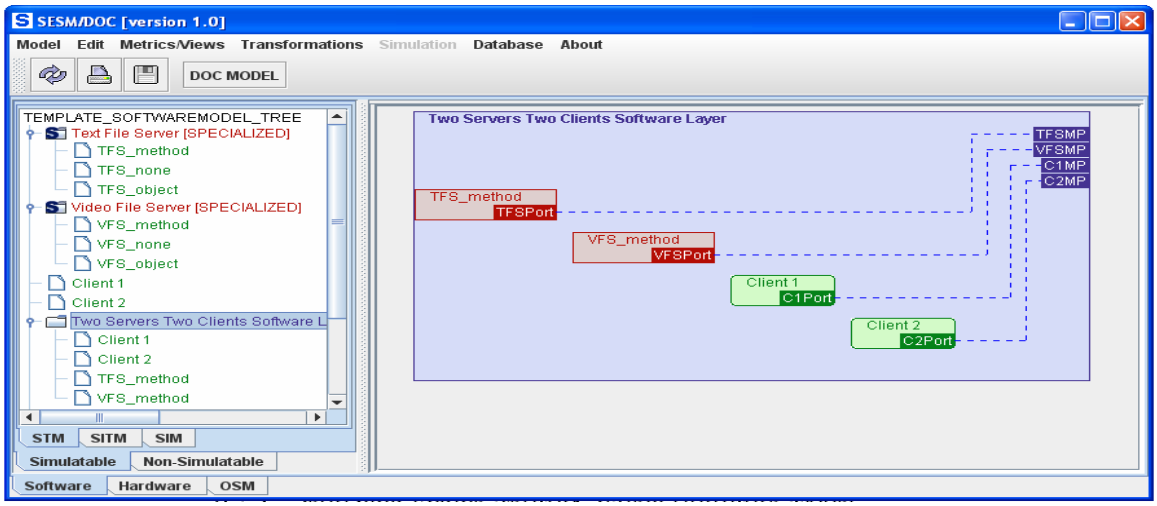


Figure 51. Software Model Coupling

6.2.4 Object System Mapping Design

In previous sections, we described how modelers use SESM/DOC to create software and hardware models. In a distributed object computing system, the separation is only one step of the system design. Another important step is object system mapping That is, when one synthesizes the distinct software and hardware models. This synthesis specifies a software layer model assignment to a hardware layer model.

In SESM/DOC, model synthesis happens in the OSM working section. The OSM model creation is similar to hardware or software model creation except that the OSM mode generation happens in the OSM working section and with the OSM model tree structure. The unique part is adding components into the system model, and how to add system mapping.

There are only two components in a system model – one software layer model and one hardware layer model. These software layer and hardware layer models are not generated in the OSM working section. In fact, they are generated in the DCO and LCN working sections. As discussed in Chapter 5, the OSM integration can choose models in the DCO and LCN tree structure to add into the OSM model. Figure 52 shows the co-design model for the “H” style network model and Figure 53 shows the co-design for the “I” style network model. The system model is the combination of the software, hardware, and object system mapping models.

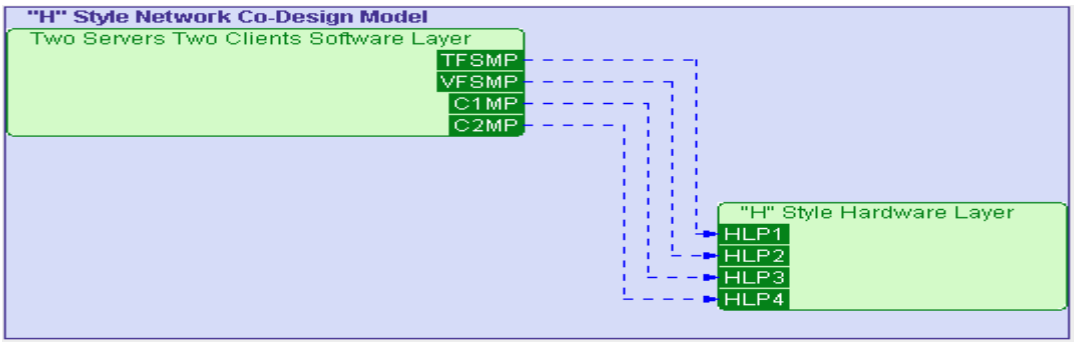


Figure 52. "H" Style OSM Model

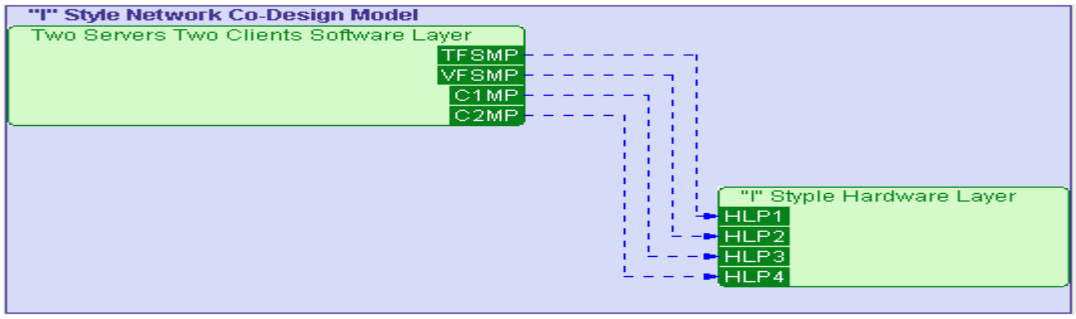


Figure 53. "I" Style OSM Model

6.3 V&V Based on Model Types and Model Constraints

The model types and model constraints, defined in section 4.3, are helpful for to the model design verification and validation. The modeler defines the constraints in an effort to ensure the model relationships are correct. SESM/DOC uses these constraints to provide help for verifying that the models generated are logically correct with respect to the DOC abstract model.

In the search engine network example, each individual model is developed as a particular model type. When the modeler attempts to created a relationship between models (either a composite relationship or an assignment relationship), the relationship

must be verified to comply with the model constraints. Otherwise, the model design is deemed incorrect regardless of the particular aspect of the system that is being modeled.

In Figure 40, the modeler adds components into a hardware group model, the processor group. According to the model composite constraints, which state that a processor group only contains processor models, the only model that can be added is the *SearchProcessor*. If a router model is added, SESM/DOC provides an error message to let the modeler know that this composition relationship is not valid. Although this is a simple constraint, it is necessary to be enforced. It helps with the model verification and validation process. Figure 42 shows five composite models (the "H" style hardware layer model, the *ProcGroup* model, the *NICGroup* model, the *LinkGroup* model, and the *RouterGroup* model). All of these composite models are valid since they satisfy the model composite constraints.

The coupling relationships in this search engine network must also be verified based on model coupling constraints. For example, in Figure 42, the *ProcGroup* model needs to be coupled with the *NICGroup* model. If the *ProcGroup* is coupled with the *LinkGroup* directly, such a coupling is invalid since the *ProcGroup* cannot be coupled directly with a *LinkGroup*. In the same model, the *NICGroup* model plays an important role by providing the media access control as discussed in Chapter 3. It must be inserted between the *PrcoGroup* and *LinkGroup*. This application of model types and model constraints aims to avoid some model design problems in a co-design network system.

6.4 Semi-automatic Simulation Code Generation

The SESM/DOC environment provides semi-automatic code generation using the facilities provided by SESM. Both the XML code and the DEVS/DOC code can be semi-automatically generated through a set of translators which query the information provided by persistent models in the database. Since models for the software, hardware, and object system models are needed, SESM/DOC provides separated name spaces (e.g. directories). The software, the hardware, and the system model code are stored in different directories. This allows the software, the hardware and the OSM models to have identical names. For example, "File Server" can be the name of a software, a hardware, or on OSM model. This naming convention avoids name collisions by providing different name spaces for the models in different model layers. Tables 16 and 17 show the generated XML file for "H" style hardware layer model, the DEVS/DOC code generated for the network interface card (primitive model) and the "H" style network co-design system model (composite model).

Table 16

Generated XML File

A piece of XML file for "H" style hardware layer model
<coupledModel name="H Style Hardware Layer_0"> <inport name="HLP1"> </inport> <inport name="HLP2"> …... <outport name="PGRP3"> </atomicModel> <atomicModel name="Processor_3">

```
                <inport name="LPort">
                </inport>
                <outport name="RPort">
                </outport>
              </atomicModel>
      …….
              <specialized name="NIC_1">
                <atomicModel name="NIC_RBO_u">
      ……..
```

Table 17

Generated DEVS/DOC Code

network interface card model

```
      public class nic extends ViewableAtomic{
      protected double processing_time;
      public nic(){this("nic", 0.0);
       }
      public     nic(String     name,     double
processing_time){
              super(name);
      ……..
              addInport("in1");

              addOutport("out1");
              initialize();
          }
          public void initialize(){
              super.initialize();
              phase = "passive";
              sigma = INFINITY;
          }
      ……..
          public message out(){
          }


      ……..
```

"H" style network co-design system model

```
public class H Style Network Co-Design Model
extends ViewableDiagraph{
          public H Style Network Co-Design
```

```
Model(){
         public H Style Network Co-Design
Model(String name){
             super(name);
     ……
             ViewableDiagraph Two Servers Two
Clients Software Layer_1 =  new Two Servers Two
Clients Software Layer();
             ViewableDeagraph "H" Style
Hardware Layer_1 =  new "H" Style Hardware
Layer();

             add(Two Servers Two Clients
Software Layer_1);
             add("H" Style Hardware Layer_1);
             addCoupling(Two Servers Two
Clients Software Layer_1, "C1MP", "H" Style
Hardware Layer_1, "HLP3");
             ..............
```

In SESM/DOC, the code generated for the primitive model is the partial code. It contains the model's input/output interface. The code generated for the composite model represents all components and their relationships. Given the semi-automatically generated code, code can be finished manually to produce the simulation models. Each of the software, hardware, and OSM layer models, can be completed using non-visual tools (e.g, Eclipse). The completed code can then be simulated in DEVS/DOC.

6.5 System Analysis

The system development includes both design and analysis. There can be multiple model candidates. Each model candidate has its own software and hardware topologies/configurations, assignment of software components to hardware components given alternative aspects of a system, or level of detail contained in individual

components of the system model. One of the benefits of the separation of software and hardware is that it is straightforward to consider how software or hardware affects one another or the system model. In particular, simulation models can be generated, simulated, and analyzed for purposes such as the performance modeling which is described next.

6.5.1 System Simulation Experiments Set-Up

Each of the experiments provides a search engine application: the clients choose a search key word and then make a search in the networks, the request will be routed to the right server which provides the search service to the search request. To be a meaningful computer network, it must have at least one server, one client, two processors, one link and two network interfaces. OSM allows multiple software mappings to the same hardware, so the possible experiments of software/hardware component ratios can be found in the up-right zone within hardware/software boundaries, as shown in Figure 54. In this section, five experiments are studied. The component configurations for the five experiments are shown in Table 18. Based on the table below, the five experiments can be traced in Figure 54.

Table 18

Experiments Settings

	LCN Layer				DCO Layer		OSM
component	Processor	Link	Router	Network interface	sever	client	
Experiment1	10	2	1	10	2	8	Software for both servers and clients mapping to
Experiment2	10	5	2	10	2	8	

Experiment3	16	15	0	16	1	15	processors
Experiment4	16	15	0	16	1	15	
Experiment5	3,…,10^3	1	0	3,…,10^3	1	2,…,999	

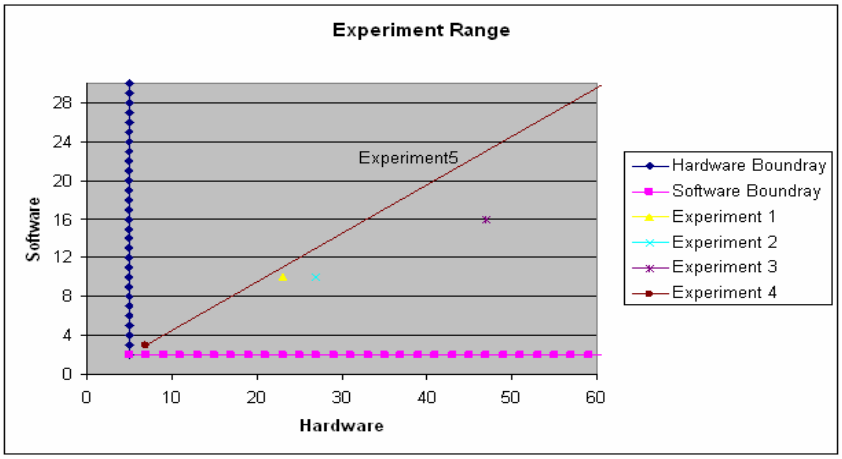


Figure 54. Experiments Boundary

In the following sections, the results of the five experiments are examined. The first two experiments show how the change of hardware topology (with the same software running inside) affects the system performance. The third experiment shows how different software configurations in the same hardware topology affect the system's performance. The fourth experiment shows the performance changes due to the ad hoc reconfiguration of the system. The last experiment addresses the scalability issue. All of the experiments are done on a PC with a P4 3.2 GHz CPU, and 1 GB memory. Data are collected based on 10 time runs of each simulation.

6.5.2 Alternative Hardware Network Analysis

As discussed above, manipulating hardware and software separately is one benefit the modeler and the designer can get from SESM/DOC. In this chapter, two experiments

are presented to show this strength based on the “H” and the “I” style models that we just developed. As shown in the table above, it has two search engine servers to distribute the search workload coming from 8 clients.

One of the search engines handles the requests with a key word starting with a letter from “A” to “L”(not case sensitive), or a number or any symbol; the other server handles the search requests with a key word starting with a letter from “M” to “Z”. The distribution of the requests from the clients is shown in Table 19.

Table 19

Search Requests Distribution

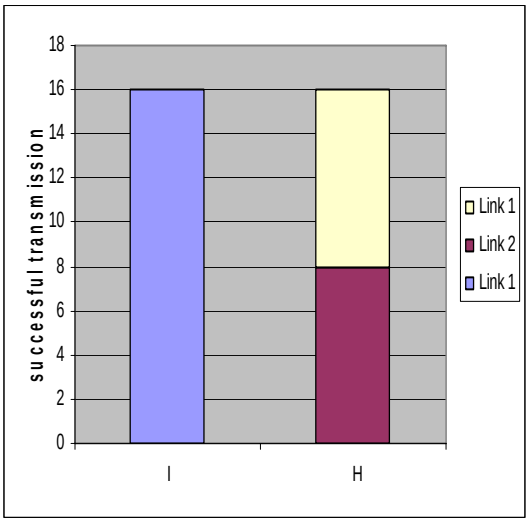
Search Client	***Search Key Word***
1	African Mountain
2	1945
3	National News
4	ASU
5	Mother Nature
6	iPod
7	Rent a Car
8	Wild Animal

The same search engine software application with the same configuration (servers and clients) is run in a different network topology which is the “H” style with a combination of shared bus topology and star topology in the second experiment.

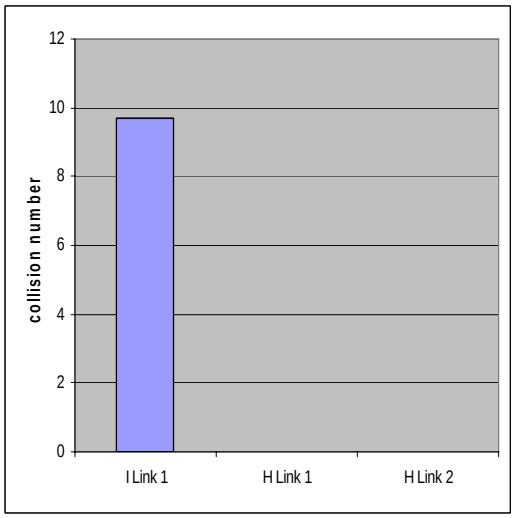
The experimental framework discussed above helps to control the simulations and collect data. In the first two experiments, link 1 in the “I” style and link 1 and link 2 in

the “H” style are the objects to be studied. They are the links connected to the search engine server and the behavior of these links is important to the performance of the whole network.

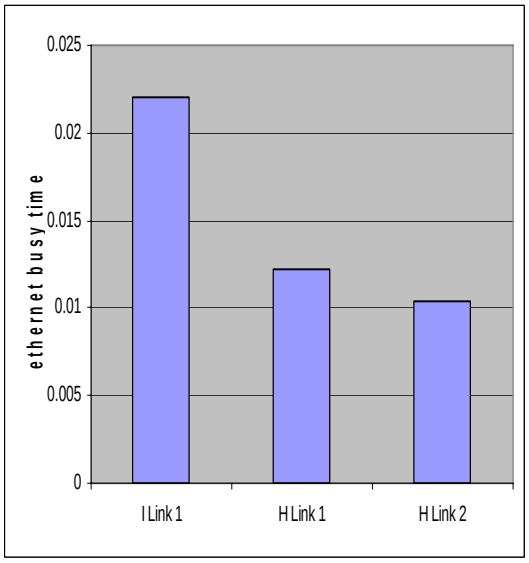
From Figure 55 (a), the successful transmission in link 1 of the “I” style is equal to the sum of the successful transmissions in link 1 and link 2 of the Hybrid Topology B. This is due to an equal transmission load in these two networks. From Figure 55 (b) it can be seen that, there are collisions in the “I” style but not in the “H” style. This is because the traffic in the “H” style is distributed in different links, and the chance for the packets to collide is much less than in the “I” style. This can also be obtained from the data in sections (c) and (d) of the figure. The links’ Ethernet busy time is much shorter in the “H” style than in the “I” style and the bandwidth utilization in the links of the “H” style is also lower than in the “I” style. Figure 55 helps to arrive at the conclusion that by distributing the network traffic, the “H” style gains shorter Ethernet busy time and much less collisions than the “I” style, while at the same time sacrificing the lower bandwidth. These comparisons are based on the same traffic load.



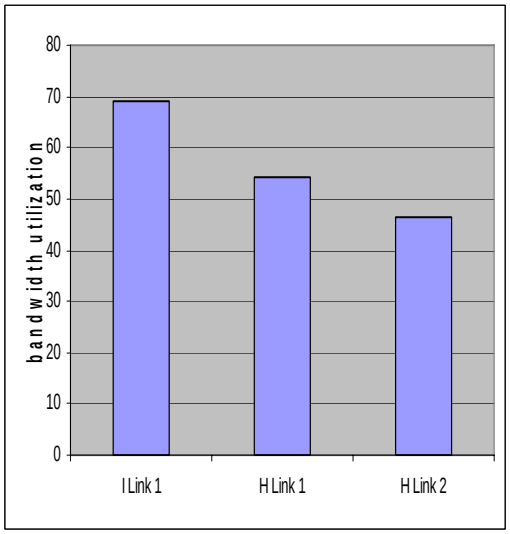
(a) successful transmission



(b) collision number



(c) ethernet busy time



(d) bandwidth utilization

Figure 55. Data Analysis for "I" Style and "H" Style

6.5.3 Alternative Software Network Analysis

With SESM/DOC, the hardware can be changed without any changes in the software to achieve a different performance. Furthermore, the different software can be exchanged to run on the same hardware to derive alternative system behaviors. In this

section, alternative software applications are simulated with a consistent hardware topology.

In order to avoid the noise from unnecessary collisions and obtain more clear data, a pure star network topology is chosen in experiment 3 to be the host where the software applications can run as shown in Figure 56.

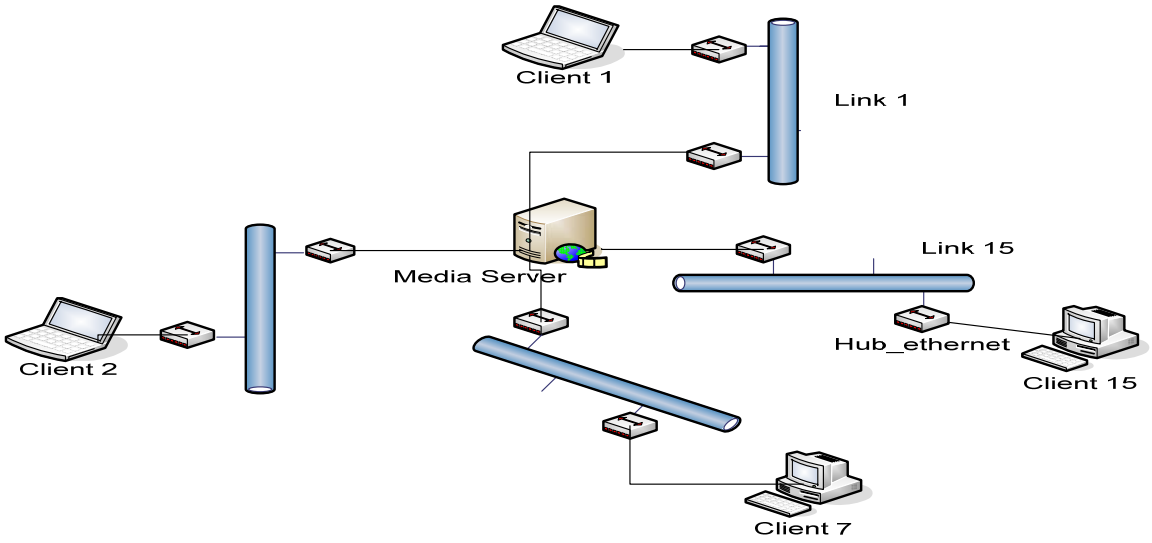


Figure 56. Star Network Topology

As discussed above, the software component in DEVS/DOC provides three working modes: none, object, and method. In none mode, one software component can only execute one job at a time and any additional requests are queued. It does not matter how many methods the software component can provide, only one job can be executed at one time. In object mode, one software component can have one job per defined method concurrently active and, for the method mode, all the incoming requests can be executed once they arrive at the hardware where the software is running. Returning back to the search engine network example, the search engine software has up to three methods to

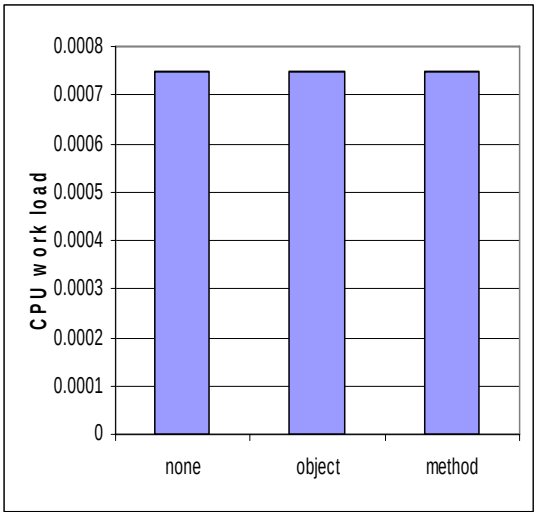
answer different search requests. Unlike the previous experiments, in experiment 3, the search engine provides both the key word driven search, and the "key word plus format" search. This can better help those clients who know more details about what they want by providing more focused search results faster. In experiment 3, the server software provides three methods to separate the request by the format they need. The first one is for a text file, the second one is for a video file and the third one is for a binary file. The 15 clients in this experiment are divided into three groups and each has 5 clients. Each of the three groups makes requests for a certain file format (text, video, and binary)

The server in experiment 3 handles the key word with the start letter from "A" to "L" and any numbers and symbols. It also handles the three different file format requests with three methods. The simulation runs 10 times for each software application mode.

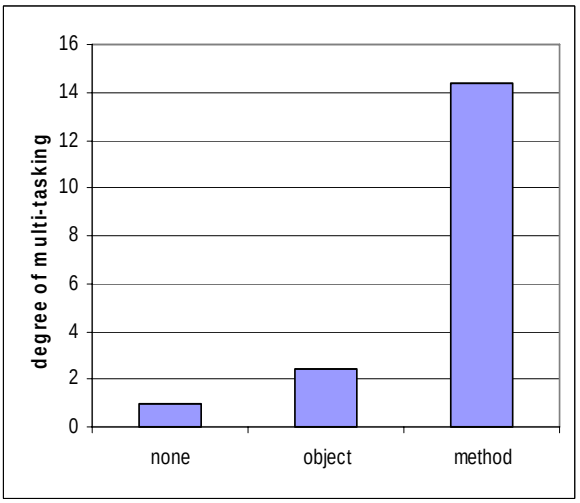
As shown in Figure 57 (a) and (b), the work load in *cpu* during the 3 modes are the same but they have a different multi-tasking degree due to their mode. This is because in DEVS/DOC, a penalty mechanism is implemented in the object and method mode which makes the object and method mode take a longer time to swap jobs in their multi-tasking *cpu*. This mechanism leads to more CPU busy time as shown in Figure 57 (c), with the same work load.

In the search engine example, one requirement is that the clients should get their search results back in a similar time. Clients have no priority in the system. To be fair, the response time should not vary too much. With 10 simulation runs for each of the three modes; the max, min and average of the response time deviations are shown in Figure 57 (d). As discussed above, in none mode, only one job can be executed in a given time, the

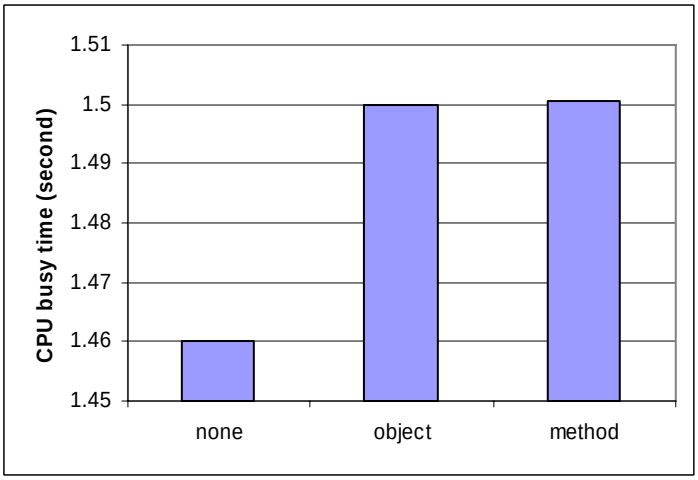
other jobs have to wait. However, in object and method mode, multiple jobs can be executed at the same time with a Round-Robin mechanism. This guarantees that all the clients will be treated fair.



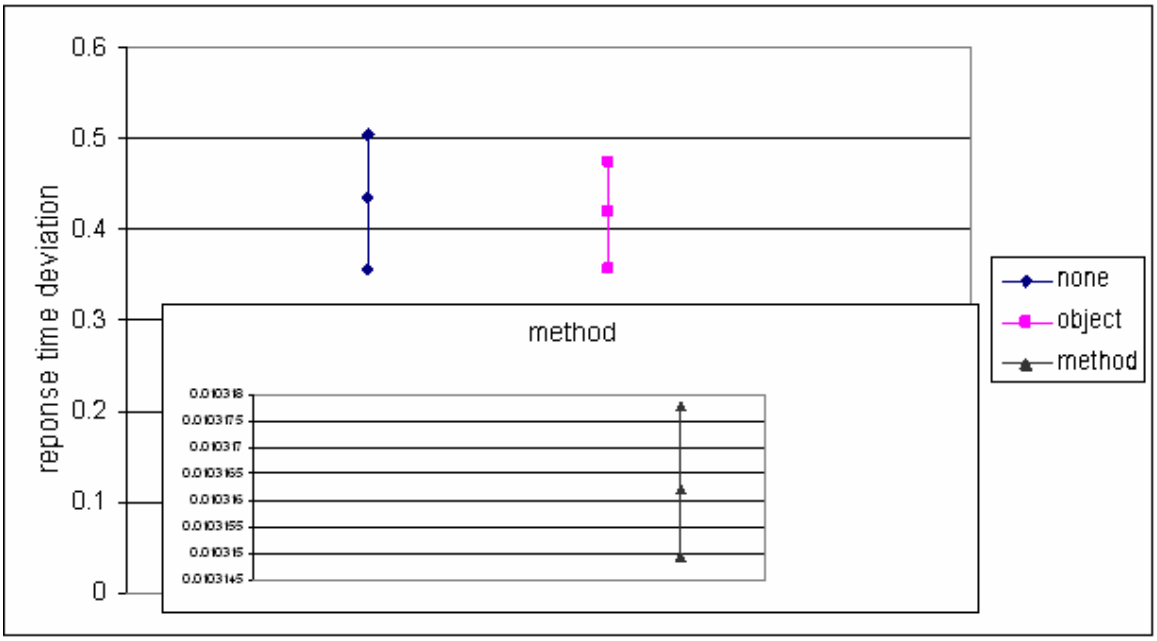
(a) CPU work load



(b) degree of multi-tasking



(c) CPU busy time



(d) response time standard deviation

Figure 57. Data Analysis for Alternative Software Applications

6.6 Summary

This chapter considers search engine network systems and develops models of these systems to illustrate how the co-design concepts, the model specifications, and the approaches provided in Chapters 3, 4, and 5, work together to design a network system model. These examples show that the co-design modeling approach enables the visual design of network systems through the separation and synthesis of models from the software/hardware model layers.

The examples show that the co-design persistent modeling approach makes the SESM/DOC environment different from all other modeling and simulation environments such as NS-2, OPNET, and TOSSIM, which store their models as files but not in the database. Compared to SESM, SESM/DOC provides the capability to separate the model

repository for different model layers. The model types and the model constraints are enforced in the SESM/DOC persistent modeling approach so that the visual modeling has the syntax and semantic information. This persistent modeling approach provides help to early stage model verification and validation which is based on these model types and constraints. The use of the database also provides a measurement of the models structural complexity.

Through the examples, it has been show that SESM/DOC provides flexibility for modelers to consider the different software and hardware configurations and topologies. This is due to the underlying SESM support for modeling families of models instead of supporting the development of individual models. SESM/DOC extends this capability for network co-design. The examples in Chapter 6 illustrate that the visual and persistent approaches in SESM/DOC help the network systems co-design modeling. The modeler can try different design options in the software and hardware models separately. This separation is a big benefit due to the complexity of the distributed co-design network. The partial co-design simulation code can be automatically generated and the structural complexity of the network models can be calculated based on the software parts and hardware parts.

7 CONCLUSION

7.1 A Comparison of SESM/DOC

This dissertation proposed a co-design modeling approach with a built-in capability to visually develop models of network systems. To support model persistence, the models are stored in a relational database. This approach has been prototyped and has resulted in the SESM/DOC environment. In this section, the dissertation work is examined in three parts. First, a selection of modeling and simulation approaches is reviewed. Second, the SESM/DOC is compared with other approaches and tools that are aimed at modeling and simulation of computer network systems. This entails some informal considerations for using modeling tools. Finally, the role of the SESM/DOC in supporting early-stage M&S verification and validation is briefly examined.

7.1.1 Modeling and Simulation Environments

To compare SESM/DOC, it is helpful to first consider modeling and simulation approaches and environments that are not specialized for network systems. This separation of *modeling* and *simulation* from one another is important in differentiating visual model development and animation of simulation models. Table 21 is used to show that different M&S approaches offer different types of support to the modelers and simulationists (Sarjoughian, Fu, Bendre, & Flasher, 2007). The purpose of this table is two-fold. First, it shows that modeling and simulation environments can be compared by considering their capabilities along. Second, experiments (use-cases) may be developed to assess the 'operational' aspects of these tools. For example, an approach and its tool

could be considered relatively simple for defining different kinds of models in a well constrained domain from pre-built components. Another approach and tool, however, could be difficult to use since models must be written in a programming language.

Clearly, developing a comprehensive evaluation across many modeling and simulation tools both from capabilities and operational aspects is very important. Undertaking such studies is outside the scope of this dissertation. Nonetheless, since Table 20 compares SESM with a select group of other popular and influential modeling and simulation tools, and that SESM/DOC is targeted for co-design modeling, we can highlight some key differences between SESM/DOC and other approaches and environments that are commonly used for modeling computer network systems.

Table 20.

Comparison of selected general purpose modeling and simulation tools (Sarjoughian, Fu, Bendre, & Flasher, 2007)

	Modeling				Simulation		
Tools	Logical	Visual	Flat Files	Database	Input/Output Animation	Run-time Visual Trajectory Tracking	Formal Specification
DEVSJAVA	Y	N	Y	N	Y	N	DEVS, OO
Tracking Environment	Y	N	Y	N	N	Y	DEVS, OO
Ptolemy II	Y	Y	Y	N	Y	Y	CSP, OO, CT, DE, DT
Simulink	Y	Y	Y	N	Y	Y	Block models, OO
SESM	Y	Y	Y	Y	N	N	System Theory, ER, OO, SES, XML

A modeling engine supports the creation and edit of logical models by guiding and enforcing structural and behavioral syntax and semantics of a modeling approach. It provides specifications of models that can be simulated. A simulation engine is responsible for executing the models that have well-defined specifications. For example, an environment such as DEVSJAVA can be considered to be a simulation engine. This is because this simulation engine is built to execute any model that is defined according to the DEVS specification. For other tools such Ptolemy II (Eker, Janneck, Lee, Liu, Liu, Ludvig, Neuendorffer, Sachs, & Xiong, 2003) and Simulink (Mathworks, 2007), it is difficult to view them primarily as either a modeling or a simulation engine. SESM is a modeling engine. This is because if we consider model development, then SESM offers more capabilities since models have logical, visual, and persistent database schema representations. On the other hand, if we consider domain-specific modeling, then Simulink and Ptolemy II offer powerful pre-built models from which complex models can be synthesized without much effort. Similarly, DEVSJAVA, Tracking Environment (Singh & Sarjoughian, 2007), and Ptolemy II, for example, support animation.

For co-design modeling and simulation approaches and tools, SESM/DOC can be used to describe a family of models with structures that conform to the DOC as well as the SESM axioms. SESM/DOC is considered a modeling engine while DEVS/DOC is considered primarily a simulation engine. The models created in a modeling engine need to persist in some fashion. Some tools such as DEVSJAVA and NS-2 store their models in flat files. The use of a database management system such as the one in SESM/DOC is important when a family of alternative models must be developed and managed. A

database helps to manage a large number of models and it simplifies the measurement of the structural complexity of the models.

7.1.2 Relating SESM/DOC with Other Network System Modeling

SESM/DOC extends SESM and emphasizes network systems co-design modeling. Table 21 presents a comparison of SESM/DOC and other network system modeling and simulation tools.

Table 21

Comparison of network system modeling and simulation tools

	Co-design Modeling			Simulation	Formal Specification
	Logical	Visual	Persistent		
DEVS/DOC	Y	N	N	Y	DEVS, DOC, OO
DEVS-NS	N	N	N	Y	DEVS, Queuing Theory, OO
NS-2	N	N	N	Y	Queuing Theory, OO
OPNET	N	Y/N	N	Y	Queuing Theory, OO
SESM/DOC	Y	Y	Y	N	Systems Theory, ER, OO, SES, XML, DOC

From a co-design logical modeling point of view, both DEVS/DOC and SESM/DOC are based on co-design logical modeling; others are not. DEVS-NS, NS-2, and OPNET can be used to develop software or hardware models, but not in a systematic way. The DOC abstract model in DEVS/DOC and SESM/DOC provide a set of well-defined concepts for co-design logical modeling. For the visual modeling, DEVS/DOC, DEVS-NS, and NS-2 provide a simulation view but not visual modeling. The model design in these tools requires representing models in programming languages. OPNET is

marked as “Y/N” because although OPNENT supports visual models development, it does not separate the software and hardware model design. Furthermore, a highly desired capability for a visual modeling engine is to generate code that can be simulated with a simulation engine. As a modeling engine, SESM/DOC can generate partial simulation code. The partial simulation code must be completed using existing IDE tools before it can be simulated in DEVS/DOC.

The latest version of the DESV/DOC environment is a portion of the work in this dissertation. To compare DEVS/DOC with these tools for logical model design support, the protocol stack plays an important role. All the computer networks modeling and simulation environments provide facilities to implement the protocol stack functionalities. Due to the critique of the description of the pure ISO/OSI model and TCP/IP reference model, the hybrid reference model is used to present the protocol stack of computer networks, as shown in Figure 58 (Tanenbaum, 1996).

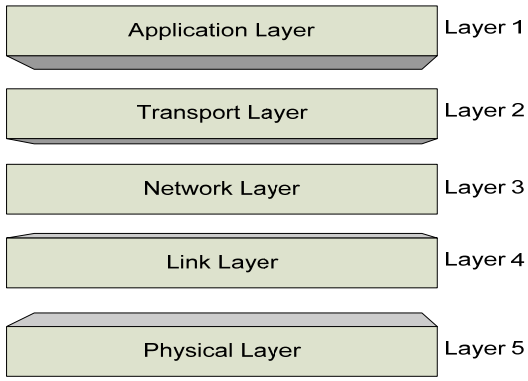


Figure 58. Hybrid Reference Model for Computer Network Protocol Stack

A detailed study of approaches such as NS-2, GloMoSim, OPNET, and QualNet, is provided in Chapter 2. These are compared in terms of the modeling which they

support for each network protocol stack layer. In Chapter 3, the DEVS/DOC implementation details are provided. DEVS/DOC shows its strength for application layer modeling with its specifications focusing on the separation and synthesis of software/hardware co-design. In the application layer, DEVS/DOC provides a computation unit for both software (DCO) and hardware (LCN) parts - the "swObject" and the "processor" class. These allow the DEVS/DOC computation unit to have more features in comparison with the node definition for NS-2, GloMoSim, and OPNET. DEVS/DOC not only provides the generation of traffic (generating messages and jobs through the network) but also has the facilities for processing the thread modes (i.e., none, object, and method) of software components. Supported by DCO (*message* and *pdu*) and LCN (*link, hub_ethernet, transport,* and *router*) components, DEVS/DOC provides multiple routing protocols and segment structures in the transport layer. DEVS/DOC also provides *unicast, broadcast* and *multicast* in the network layer and the media access control protocol in the link layer. In comparison, the NS-2 models are detailed to capture realistic functionality of protocol stacks. The summary of the discussion above and those presented in Chapters 2 and 3 is given in Table 22.

Table 22

Modeling and Simulation Supports in Network Protocol Layers

	Hybrid Reference Model Layers				
	Layer1	Layer2	Layer3	Layer4	Layer5
NS-2	Weak Support	Strong Support			
GloMoSim	Weak Support	Strong Support			
OPNET	Weak Support	Strong Support			
QualNet	Weak Support	Strong Support			
TOSSIM	No Support	Strong Support			No Support
DEVS/DOC	Strong Support			Weak Support	No Support

7.1.3 SESM/DOC and V&V

In Section 6.3, we discussed how the model types and model constraints can help with model verification and validation in the search engine network example. A complete study about the modeling verification and validation is beyond the scope of this dissertation. Here we give a brief discussion about the role of SESM/DOC in supporting early-stage M&S verification and validation. The SESM/DOC logical models are a set of model types and model constraints for modeling the software and hardware layers of network systems. The persistent modeling approach in SESM/DOC supports these model types and constraints by saving the typing and constraints information in tables with corresponding model identification. These constraints are important for validating user-defined models. During model development, the modeler's creation of models is enforced to be consistent with the SESM/DOC approach. For example, an action to add a SMA into a HLM will not be allowed based on the hardware layer model composite constraint that HLM can only contain hardware models. Similarly, every coupling connection is checked to be consistent with the allowed coupling types. For example, an action to couple a PGM to a RGM would fail verification per the constraint that processors must go through network interface cards and links to connect the routers.

By ensuring that only successfully verified composite and couplings constraints exist, the modeler is provided some level of validation of the model. The logical, visual and persistent modeling approaches with the model types and constraints for co-design network systems enables the modeler to complement the syntax and semantics of the

modeling theory with the unique information that belongs to the co-design network systems, and helps SESM/DOC support early-stage M&S verification and validation. However, the V&V support is limited to the constraints that the modeler explicitly specifies prior to model development. Validation of a system goes beyond model composition and model coupling. It requires that the modeler understand the problem, partitioned the problem appropriately, and incorporate capabilities into the models that meet the needs of the modeled system. While the visual and persistent modeling in SESM/DOC relieves the modelers from some basic steps in carrying out the verification and validation processes, many other steps must be carried out with some combination of other tools and techniques.

7.2 Summary

The widespread use of computer technology contributes to the complexity of modern systems in part due to the ever increasing functionality of software components, higher raw hardware computing and communication, and the multitude of ways software and hardware components are integrated. An embedded system, which combines the software and hardware components into one system, is a typical kind of system in which software and hardware interact in complex ways to achieve their intended functionality. Development of such systems poses a wide variety of challenges to designers. In particular modelers need to develop software and hardware component models which generally have mutually exclusive constraints and yet have to be integrated to satisfy mixed system requirements.

Similarly, powered by the rapid advance of distributed computing, and network technology, embedded systems are networked together more and more; creating increasingly complex structures and behaviors. For network systems, it is useful to separate the software components and hardware components for design and analysis purposes. The combination of software and hardware, together with distributed processing, make the distributed co-design network challenging to design and difficult to analyze. As a result, we examined modeling of network system from a co-design perspective where both the separation and the synthesis of software and hardware components in order to make rigorous system model design is required and; therefore, they have become very important in model driven engineering, and more specifically simulation-based design.

There are many modeling and simulation approaches to help with the process of large-scale and complex system design and analysis. Some of them are designed for centralized embedded systems. However, few of modeling and simulation approaches focus on decentralized or distributed co-design network systems. Most current modeling and simulation approaches fall short of the requirements for presenting the software aspects and hardware aspects of the system separately, satisfying software and hardware requirements as well as the assignment of software components to hardware components of networks systems. Satisfying separate and combined software and hardware layers of system requirements is important for generating models that can be simulated.

This dissertation presented a co-design approach for developing models for the software and hardware layers models of distributed systems. Based on a set of model

types, this modeling approach separates software and hardware models into their logical, visual, and persistent models. For the logical model, this approach uses DOC abstract models (DCO, LCN, and OSM) which are specified using the DEVS specification, to define software model and hardware model. The logical constraints belonging to software, hardware, and their mappings are incorporated into the SESM visual and persistent modeling. The hierarchical component-based block and tree structure visual modeling were developed to support the distinct DOC co-design requirements. The visual model presents the components of the model and the relationship among models through coupling and mapping. The visual model provides different levels of model decomposition so that different aspects and resolution of model can be viewed. Three sets of database schemas for the software model, the hardware model and the synthesized system model are developed. The use of schemas ensures the systematic co-design for network systems. The separated persistent model approach provides flexibility in the sense that changes in software model data schema and changes in hardware model data schema do not affect each other.

Based on the proposed approach, we have developed SESM/DOC, which is an environment to support visual and persistent modeling for distributed network systems. The environment is an extension of SESM. The logical, visual and persistent models in SESM are extended to support the domain-specific model concepts (DCO, LCN, and OSM) defined in DOC. The simulation model of DEVS/DOC can be partially generated with the SESM/DOC. This relieves modelers from having to develop DEVS/DOC source

code from scratch. After the partial source code is completed, the simulation model can be executed in the DEVS/DOC environment.

In SESM/DOC, models are divided into a software layer model, a hardware layer model, and a system layer model. These different model layers are developed within their own working sections and support modeling complex network systems. The visual models for software and hardware are developed in a software model working section and a hardware model working section separately. The system model is synthesized in the system working section. This approach helps the modeler focus on what they want to work on, either software models, hardware models, or the synthesized system model, and not be interrupted by different model constraints from other model layers. In the system model working sections, the system model is synthesized by mapping a chosen software model from software model candidates in the software working section onto a chosen hardware model from hardware model candidates in the hardware working section. In both the software and hardware working sections, model decomposition and specialization can be used to generate a model family for alternative system model design. In the composite model and system mapping model, alternative system model design can be realized by choosing a different specialized model from the same model family. This distinguishes SESM/DOC from other modeling tools which lack a framework to develop alternative model specifications in a disciplined fashion.

The software, hardware and synthesized system models that are designed in separated working sections are each saved in their own database tables. The database implementation enables the SESM/DOC environment to handle large-scale models. The

database records the modeling information in the logical model so that it can be used to calculate the number of models, ports, and couplings. This provides an important measurement of the system structural complexity.

With the ability to specify component-based models for a network system, the SESM/DOC modeling approach has been developed based on the abstract distributed object computing specification. Through the distributed co-design modeling example for the searching engine network system, the software component model, the hardware component model and the integrated system model are developed separately. Alternative software models and alternative hardware models can be developed and chosen based on a set of well-defined, general-purpose hierarchical (multi-resolution/multi-aspect) modeling constraints, and can be synthesized as a different network system. The SESM/DOC environment has been extended for the domain of network systems and support modeling system networks that can be specified according to the DOC abstract model and in particular models specified for simulation in DEVS/DOC. The structural complexity metrics provided by the database can be used to evaluate the structural complexity of network systems. The SESM/DOC approach is targeted for complex systems (e.g., enterprise command and control) where key architectural decisions (e.g., service-oriented architecture)(Tsai, Chen, Paul, Zhou, & Fan, 2006) and computing technologies (e.g., grid computing) are key for concept development and early design stages.

As part of this dissertation and important for SESM/DOC, we also ported the distributed object computing abstract models with DEVSJAVA 3.0 and JDK 1.5.

DEVSJAVA 3.0 and JDK 1.5 provide a new set of object collections and a user interactive console for DEVS/DOC 2.0 simulation. This new DEVS/DOC implementation is important because once the SESM/DOC partially generated simulation code has been completed, the network system model can be simulated.

7.3 Future Works

SESM/DOC is the approach to develop distributed co-design models by implementing multiple modeling layers in SESM. Since SESM/DOC supports independent modeling of software, hardware, and system level modeling, it can be extended with new model types, and therefore, offer additional modeling capabilities.

Multiple Domains Modeling and Simulation: For a Distributed Co-design System: The SESM/DOC co-design modeling approach has been developed based on the abstract distributed object computing specification. It provides partial code generation based on the DEVS specification because DEVS/DOC is the implementation of the DOC abstract model with DEVS specification. In the future, it is good to extend SESM/DOC with other modeling and simulation specifications so that multiple domains modeling and simulation approaches can integrate together for distributed co-design modeling. For example, a set of discrete time specified software models may need to be mapped into a set of discrete event specified hardware models to build a multiple domain distributed co-design system.

Model Dynamic Properties Presentation: SESM/DOC provides the structure properties for a distributed co-design system. It also has the facilities to add state

variables into software models and hardware models. In order to present the model's dynamic properties, the model state transaction needs to be addressed. In a distributed co-design system, the software and hardware have different states and the state changes in software components may or may not lead to the state change in hardware. Also, the state changes in the hardware components may affect the state in the software components. To give a complete set of state transactions for software and hardware components is good for tracking the whole system's state changes and for analyzing the dynamic properties of the co-design system. Presenting model state transactions is also important for distributed co-design modeling verification and validation in the sense of checking if the state transaction leads the system to the correct state (Schulz, Rozenblit, & Buchenrieder, 2002).

Distributed Co-design Modeling Verification and Validation: SESM/DOC is well suited for system architecture specifications. The separation of concern afforded by SESM/DOC is important for model validation, verification, and accreditation (VV&A). Since verification and validation is difficult for large-scale complex systems, the disciplined approach supported by SESM/DOC provides a foundation for separating software and hardware as well as synthesized system software/hardware VV&A. The current SESM/DOC provides distributed co-design modeling constraints which are helpful to V&V. It is not trivial and important in the future to provide more rigorous semantics and syntax modeling verification and validation for distributed co-design modeling. Model checking approaches will need to be added into SESM/DOC to guarantee a models' correctness.

Integration with Other Approaches: SESM/DOC provides visual and persistent modeling for a distributed co-design system. It will be helpful for SESM/DOC to integrate with other approaches such as IBM Eclipse and DEVS Simulation Tracking Environment to get more facilities for modeling. Eclipse can provide a powerful Integrated Development Environment (IDE) for the modeler to complete the partially generated simulation code from SESM/DOC. The completed simulation code can be compiled and run in Eclipse environment. Eclipse also provides numerous plug-ins which may be used with SESM/DOC. DEVS Simulation Tracking Environment provides a DEVS simulator and an analysis tool which tracks model state variable status for the simulation model.

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