SYSTEMS ENGINEERING PROCESS MODELING AND SIMULATION

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ABSTRACT

SYSTEMS ENGINEERING PROCESS MODELING AND SIMULATION

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In this study, an approach is proposed to model and simulate the systems engineering process of design projects. One of the main aims is to model the systems engineering process, treating the process itself as a complex system. A conceptual model is developed as a result of a two-phase survey conducted with systems engineers. The conceptual model includes two levels of activity networks. Each first level systems engineering activity has its own network of second level activities. The model is then implemented in object-oriented modeling language, namely SysML, using block definition diagrams and activity diagrams. Another aim is to generate a discrete event simulation model of the process for performance evaluation. For this purpose the SysML model is transformed to an Arena model using an Excel interface and VBA codes. Three deterministic and three stochastic cases are created to represent systems engineering process alternatives, which originate from the same conceptual model but possess different activity durations, resource availabilities and resource requirements. The scale of the project and the effect of uncertainty in activity durations are also considered. The proposed approach is applied to each of these six cases, developing the SysML models, transforming them to Arena models, and running the simulations. Project duration and resource utilization results are reported for these cases.

Keywords: Systems Engineering, Object-oriented Modeling, SysML, Discrete Event Simulation, Arena

ÖZ

SİSTEM MÜHENDİSLİĞİ SÜRECİNİN MODELLENMESİ VE SİMÜLASYONU

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Bu çalışmada tasarım projelerine ait sistem mühendisliği sürecinin modellenmesi ve simülasyonuna yönelik bir yöntem önerilmektedir. Temel amaçlardan biri, sürecin kendisini karmaşık bir sistem olarak ele alarak sistem mühendisliği sürecini modellemektir. Sistem mühendisleri ile gerçekleştirilen iki aşamalı anket çalışmasının sonucunda bir kavramsal model elde edilmiştir. Kavramsal model, iki seviye aktivite ağı içermektedir. Her bir birinci seviye sistem mühendisliği aktivitesi, kendine ait ikinci seviye aktivite ağına sahiptir. Daha sonra model, nesne yönelimli modelleme dilinde, SysML üzerinde, blok tanımlama diyagramları ve aktivite diyagramları kullanılarak uygulamaya geçirilmiştir. Diğer bir amaç ise performans değerlendirmesi için sürecin ayrık olay simülasyon modelini oluşturmaktır. Bu amaçla, Excel ara yüzü ve VBA kodları kullanılarak SysML modeli bir Arena modeline dönüştürülmüştür. Aynı kavramsal modelden gelen fakat farklı aktivite süreleri, kaynak miktarları ve kaynak gereksinimlerine sahip olan sistem mühendisliği süreç alternatiflerini temsil etmek üzere üç deterministik ve üç stokastik durum oluşturulmuştur. Projenin büyüklüğü ve aktivite sürelerindeki belirsizliğin etkileri de dikkate alınmıştır. Önerilen yaklaşım, SysML modelleri oluşturmak, bu modelleri Arena modellerine dönüştürmek ve simülasyonlar gerçekleştirmek yoluyla altı durumdan her birine uygulanmıştır. Bu durumlar için proje süresi ve kaynak kullanımı sonuçları raporlanmıştır.

Anahtar Kelimeler: Sistem Mühendisliği, Nesne Yönelimli Modelleme, SysML, Ayrık Olay Simülasyonu, Arena

To My Family

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CHAPTER 1

INTRODUCTION

Systems modeling is a method, which is used to conceptualize a system whenever needed during its life cycle. Modeling has been conducted mainly in functional (algorithmic) fashion building the system on several system functions, until an object-oriented modeling approach is introduced. Object-oriented approach treats a system part not only as a part of its functionality but also as a component within the overall system structure. In software development domain, an object-oriented modeling language has been widely used as a standard – Unified Modeling Language (UML). However, today's complex systems are not only software systems. Complex products such as automobiles, aircraft or space vehicles also require systems modeling tools and methods, which allow them to be analyzed, integrated and tested in an object-oriented manner. Therefore, systems engineering domain also needed a standard language to manage the design and integration of complex systems. Systems Modeling Language (SysML) was introduced as a result of this need. SysML is based on UML and is obtained by modifying UML to include certain additional features regarding systems engineering domain and to exclude certain UML features since they are not needed in systems engineering domain.

Taking a closer look at systems engineering, its aim is to achieve successful systems. The success criterion is not only to produce a functional product but also to assure user satisfaction while staying within cost and budget limitations. The time period to conduct systems engineering can be extended to the product's life cycle. Therefore, the process of managing complex systems can be regarded as a complex system itself.

Object-oriented modeling with SysML provides modeling the system in terms of behavior and structure. It also facilitates observing the system in any abstraction level. SysML includes different types of diagrams, which reflect different system aspects and thus provide good interface to any parties, including systems engineer(s), project manager(s) and subject matter expert(s) obtaining his or her requirements via the systems engineer.

If the system of concern is a process composed of several activities, discrete event simulation of the system provides an important aid in order to observe the effects of different parameters on the duration of the process and the resource usages. In this case, simulation is a good way of analyzing the systems engineering process alternatives and verifying the object-oriented model. Since the object-oriented modeling environment and the simulation environment are different, the necessary features of the object-oriented model should be transferred to the simulation environment for the simulation model to be built and run. Automating this process as much as possible becomes a concern in terms of efficient modeling and management of systems.

This thesis study considers the systems engineering process of a real-life design project, including the post-design phases, as the system of concern. The typical project of concern aims at the design of aerospace products of different scale. The main purpose is to provide a generic method to model and simulate the systems engineering process of a design project. While doing this, the activities in the process and their precedence relations are needed. These are not taken arbitrarily or a specific reference is not directly used. Instead, a conceptual model for the systems engineering process of a design project is also developed in this study.

The conceptual model of systems engineering process is based on two well-known references: INCOSE [1] and Georgia Tech [5]. Activities from these references are presented to a group of systems engineers working at Turkish Aerospace Industries Inc. and a two-phase survey is conducted. At the end of the survey study, activity networks from respondents are collected and analyzed to obtain a unique first level systems engineering process model. The first level activities in this network model are further detailed to obtain the second level networks. This study considers two levels of activity networks. The first reason for this is that the two references above are clear enough to define the activities within any high level activity and hence they can provide activity definitions in two levels. The second reason is that further decomposition would reduce the generality of the conceptual model by including specific information. Finally, it would not be practical to assign parameter values to the activities that are detailed too much, i.e. assigning duration information to a second level activity is reasonable while it may not be reasonable for a third level activity.

The conceptual model is implemented in SysML using the tool IBM Rational Rhapsody. The reason for selecting Rhapsody is that it is a widely-used commercial tool, which is also used in Turkish Aerospace Industries, Inc. Block Definition Diagrams are used to reflect the system hierarchy, and Activity Diagrams are used to describe the precedence relations and the activity networks. The SysML model is to include the parameters to which different values can be assigned in order to obtain different modeling alternatives. These parameters are selected as duration and resource requirements of each second level systems engineering activity. Initial values are set and used during the model building process. Arena Simulation Software is used as the simulation software.

There are several methods to conduct transformation from the object-oriented modeling environment to the simulation environment. An applicable method uses XML Metadata Interchange (XMI) interface of Rhapsody, Microsoft Access interface of Arena and XMI conversions. In this study a different approach is proposed. On the Rhapsody side, table view is used to monitor activity names and parameters required for simulation purposes. On the Arena side, the conceptual model is implemented and, by exporting this model to Microsoft Excel, a base Arena model is obtained. Then, the table view in Rhapsody is transferred to an Excel file. A series of Visual Basic for Applications (VBA) codes are run on the exported table view and the base Arena model, and finally the model to be imported to Arena for simulation is obtained. Importing this Excel file to Arena, simulation is conducted and results are obtained.

In order to verify and evaluate the overall method, which includes systems engineering process modeling and simulation, a case study is conducted. Three sample cases are specified in terms of durations and resource requirements of activities. These are: small scale and low resource availability, large scale and low resource availability, and large scale and high resource availability cases. In terms of activity durations, the number of cases is extended to six in order to include both deterministic and stochastic activity durations. Hence, the effect of uncertainty in the activity durations is taken into account. Triangular distribution is used for stochastic activity durations. Low and high risk activities are distinguished by the maximum values used for triangular distribution. The overall transformation process is followed for these six different cases, simulation results are obtained and compared.

The proposed approach is considered as applicable to project management problems. It provides certain advantages over the well-known project management tools and methods. Firstly, the process of concern is specified as a design project in aerospace domain and the approach is based on a survey study conducted with people who have been working in a real life aerospace design project. The experiences of the respondents are also evaluated. Hence, a realistic process network is achieved in the domain of concern. Secondly, the approach allows conducting sensitivity analysis by assigning different resource availabilities and different resource requirements and durations for the activities. Hence the proposed approach does not address a pure scheduling solution but also provides means for "what if" analysis facilitating workload and activity duration estimation. Finally, the object-oriented methodology provides future extension capabilities to include the physical model of the product and link it to the processes obtained in this study. Therefore, an approach which is applicable to management of design projects in aerospace domain and which provides means for sensitivity analysis including certain future extension capabilities is proposed.

In Chapter 2 of this thesis, a literature survey is introduced. In Chapter 3, the conceptual model formation process is described and the proposed conceptual model is presented. Chapter 4 includes implementation of the conceptual model in SysML. Transformation of the SysML model to the Arena simulation model is given in Chapter 5. Case studies and results are provided in Chapter 6. Finally, In Chapter 7, concluding remarks and future perspectives are provided.

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CHAPTER 2

LITERATURE REVIEW

In this chapter, a literature review is presented in three sections. In Section 2.1, systems engineering concept is introduced. In Section 2.2, object-oriented modeling is presented together with the modeling languages UML and SysML. Finally, studies related with model transformation from object-oriented modeling environment to simulation environment are provided in Section 2.3.

2.1 SYSTEMS ENGINEERING CONCEPT

Concepts of "system" and "systems engineering" are described in different ways by certain well-known references. In this section, first the definitions are introduced and then systems engineering process and related activities are presented from the perspective of several references.

International Council on Systems Engineering (INCOSE [1]) defines a system as "an integrated set of elements, subsystems or assemblies that accomplish a defined objective", where elements might be processes as well as products (i.e. hardware, software etc.). Similarly, in MIL-STD-499B [2] it is stated that a system is "an integrated composite of people, products and processes that provide a capability to satisfy a stated need or objective." Weilkiens [3] places an emphasis on the aspect that the common goal of the system cannot be achieved by any of the components or blocks of the system individually.

A system is more than its elements since the interactions of system elements can lead to complexity and difficulties in control, as stated in Weilkiens [3]. It is specified by Arnold and Lawson [4] that the interrelationships among the system elements determine properties at the boundary of the system. Weilkiens [3] evaluates that increasing complexity in systems, increases the need for a holistic approach. Based on the definitions of system, systems engineering can be regarded as an interdisciplinary approach, which pursues realization of successful systems as described in INCOSE [1]. According to the definition of INCOSE [1], systems engineering considers technical and business needs of customers to provide a quality product satisfying these needs. User aspect is also highlighted in MIL-STD-499B [2], by defining systems engineering as "an interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and life-cycle balanced set of system product and process solutions that satisfy customer needs." Weilkiens [3] mentions that systems engineering is on the stage, from the idea of creating a system to system disposal.

Systems engineering process is named as *SIMILAR* in Weilkiens [3]. The name is an abbreviation, denoting the first letter of each systems engineering task. Tasks and a very brief summary of corresponding meanings are provided below:

- State the problem: This task includes defining what the system will perform and which requirements the system will meet.
- Investigate alternatives: This task includes evaluating system alternatives and weighing them considering criteria such as cost, weight, size, etc.
- Model system: This task includes creating system models of selected solutions in order to be used for system design and also in order to be used during system's life cycle.
- Integrate: This task includes integrating the systems by defining system interfaces with its environment etc.
- Launch the system: This task includes creating the system based on a specified design solution and letting the system begin its operation. Implementation requirements should be referenced.
- Assess performance: This task includes testing and measuring the performance of the system. System requirements should be referenced.
- Re-evaluate: This task includes verifying and evaluating the results of the process and providing feedback to the process.

INCOSE [1] groups system life cycle processes considering four perspectives as: Project Processes, Technical Processes, Organizational Project-Enabling Processes and Agreement Processes. These processes are not allocated to life-cycle stages, they are considered to be applicable to all stages as appropriate to the nature of the project [1].

INCOSE [1] Technical Processes are given below including the purpose of each process:

1. Stakeholder Requirements Definition: "Define the requirements for a system that can provide the services needed by users and other stakeholders in a defined environment"
2. Requirements Analysis: "Transform the stakeholder, requirement-driven view of desired services into a technical view of a required product that could deliver those services"
3. Architectural Design: "Synthesize a solution that satisfies system requirements"
4. Implementation: "Realize a specified system element"
5. Integration: "Assemble a system that is consistent with the architectural design"
6. Verification: "Confirm that the specified design requirements are fulfilled by the system"
7. Transition: "Establish a capability to provide services specified by stakeholder requirements in the operational environment"
8. Validation: "Provide objective evidence that the services provided by a system when in use comply with stakeholders' requirements, achieving its intended use in its intended environment"
9. Operation: "Use the system in order to deliver its services"
10. Maintenance: "Sustain the capability of the system to provide a service"
11. Disposal: "End the existence of a system entity"

INCOSE [1] Project Processes are given below, by just their names without mentioning the details of each process:

1. Project Planning Process
2. Project Assessment and Control Process
3. Decision Management Process
4. Risk Management Process
5. Configuration Management Process
6. Information Management Process
7. Measurement Process

INCOSE [1] Organizational Project-Enabling Processes are given below, by just their names without mentioning the details of each process:

1. Life Cycle Model Management Process
2. Infrastructure Management Process
3. Project Portfolio Management Process
4. Human Resource Management Process
5. Quality Management Process

INCOSE [1] Agreement Processes are given below, by just their names without mentioning the details of each process:

1. Acquisition Process
2. Supply Process

Georgia Tech [5] categorizes systems engineering processes in a very similar approach to INCOSE [1] except including “Enterprise Processes” instead of “Organizational Project-Enabling Processes”. It is stated that these processes are used where needed during the life cycle [5].

Georgia Tech [5] Systems Engineering (Technical) Processes are given below including the purpose of each process:

1. Mission Analysis: “Determine problem / opportunity, identify potential customers and stakeholder, collect high-level desirements”
2. Requirements Analysis: “Define system customers, determine requirements from desirements, validate system requirements with system customers”
3. Baseline Management: “Establish initial system baselines, control changes to baselines as system definition matures”

4. Functional Analysis: “Identify system functionality in generic terms, validate completeness of functional system description”
5. Tradeoff Studies: “Study various means of providing system functionality, remove unacceptable candidates from further consideration, identify any risks associated with acceptable functional candidates”
6. Alternative Analysis: “Combine acceptable functions into alternative total system solutions, assess performance of system alternatives, select one or more preferred solutions”
7. System Synthesis: “Identify physical components of preferred system solution(s), develop physical system architectures”
8. Systems Integration: “Define interfaces between physical system components, define interfaces between system and environment, determine controls and characteristics of all interfaces”
9. System Verification: “Test, inspect, simulate, etc. the physical architecture of preferred system solutions, identify and resolve any non-compliance with requirements”
10. Systems Engineering Planning: “Plan for the total systems engineering effort on a project, integrate with project management activities”

Although definitions for system and systems engineering differ among the references, they provide a common understanding for systems engineering concept. INCOSE [1] and Georgia Tech [5] together form a baseline for our conceptual model for Systems Engineering Process. A subset of methods and tools to enable systems engineering process are provided in the next section, Section 2.2.

2.2 OBJECT-ORIENTED MODELING, UML AND SysML

As explained in Weilkiens [3], systems engineering approach needs special tools and methods to manage the complexity in systems. In accordance with this need, the evolution of software tools from punch cards to procedural programming languages and object-oriented languages is highlighted [3].

As Booch [6] states, in order to design a complex system, the system should be decomposed into smaller parts. This decomposition can be done in two ways:

algorithmic or object-oriented. In algorithmic decomposition “each module in the system denotes a major step in some overall process” as described by Booch [6]. However, in object-oriented decomposition an agent, which both possesses behavior and models an object of real life, is considered rather than considering a “step” in the problem. Booch [6] concludes that object-oriented view is better to manage the inherent complexity in systems from software perspective, allowing reuse of common practices and building confidence as the system grows incrementally. In accordance with the information included in Booch [6], it is stated by Weilkiens [3] that with increasing abstraction, the system appears to be simpler, providing a concrete state on any abstraction level.

The object-oriented Unified Modeling Language (UML) [7] [8], which is being used in software development, has become a very popular programming language as described in Weilkiens [3]. Moreover, it is stated that systems engineering domain was lacking a standard language and this situation was leading to difficulties in interdisciplinary projects. Increased complexity required defining components and sharing them among teams, as explained in Weilkiens [3]. On the other hand, building the shared language on a pre-existing one would increase the speed of the whole process. Therefore, having extension capabilities, UML was taken as a basis and Systems Modeling Language (SysML) was created [9].

SysML Specification [9] includes SysML diagram taxonomy as given in Figure 2.1. The figure includes the differences with respect to UML2.

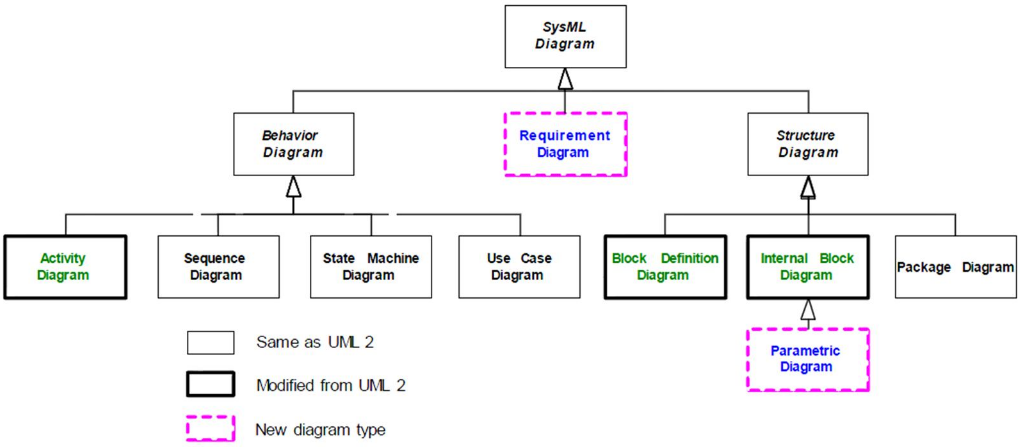


Figure 2.1 SysML Diagram Taxonomy [9]

Different types of diagrams given in Figure 2.1 are used to model different components or aspects of a system. However, they are related and they should be consistent with each other. In this work, mainly the activity diagram is used, details of which will be given later.

Although software systems are complex and need to be managed systematically, systems engineering issues differ from the software domain due to interaction of hardware and software of complex systems, and even the human and processes using the systems, as described in Weilkiens [3]. In addition, it is stated in Weilkiens [3] that SysML is not just another software development language but a language to model all the factors in the scope of engineering a complex system.

Since our system-of-interest is the systems engineering process of a design project, which encompasses high and low level systems engineering activities, and related resource and duration requirements, it is regarded as a complex system in systems engineering domain. Therefore, object-oriented modeling and SysML are regarded as applicable methods/tools for our study.

2.3 MODEL TRANSFORMATION FOR SIMULATION PURPOSES

Regarding complex systems management, Weilkiens [3] states that it is a good idea to first design the system and then simulate it before implementing and using. Having provided systems engineering concepts, object-oriented methodology and SysML in previous sections, we present several studies related with transforming object-oriented models to simulation models in this section.

Anglani et al. [10] introduced a procedure for flexible manufacturing systems simulation model development using object-oriented approach of UML together with transaction-oriented Arena simulation language. One of the main motivations of the study was the difficulty in transforming system requirements into the simulation program when current simulation methods are followed. By using the object-oriented approach, where each component of the system was translated to an element of the code (object), Arena programs were constructed in compliance with the requirements.

The proposed model - UMSIS (UML Modeled SIMAN Implemented Simulation software) is composed of four phases. The first three of them are related with conceptual model formation and the last phase is about the implementation of this model in the simulation environment.

First step of conceptual model formation was described as the functional model design, where use case diagrams of UML were used to identify the components and use cases. Therefore, a static representation of the system was presented and what the system does was clarified. Secondly, a dynamic model was developed by using UML interaction diagrams (both sequence and collaboration). Hence, the relationships of the components were defined while answering how use cases were performed. The third phase was the object model design, where the internal structure and relationships of the components were specified via UML class diagrams. UMSIS was regarded as an iterative but not sequential approach.

Conceptual model formation was followed by the last phase, formal model implementation. In this phase, simulation code is built by using the following mapping:

1. Mapping between the static characteristics of UML object classes and ENTITIES and/or ELEMENT modules of Arena.
2. Mapping between the dynamic characteristics of UML object classes and BLOCK modules of Arena.

By UMSIS procedure, Anglani et al. [10] presents a methodology for FMS modeling in UML and implementation of the model to be simulated in ARENA.

Constant et al. [11] developed a tool to automatically translate UML2 models to a commercial simulator, HyPerformix Workbench. The models of consideration were related to service-oriented systems, where performance analysis was the main concern for design and development of the system. The tool’s front-end interface was provided via a UML2 profile for the Eclipse-based Rational Software Modeler. Use Case Diagram, Activity Diagram and Deployment Diagram were used, while extending the UML profile to include certain performance information, i.e. probabilistic request arrival times in Use Case Diagrams, resource consumptions in Activity Diagrams and so on.

The intermediate metamodel was based on Petri nets and Queuing Networks. The transformations from UML2 model to the intermediate meta model and from the metamodel to the simulator were conducted with ATLAS Transformation Language. The tool provided a file with graphical layout information, which was supported to operate with Workbench simulator. Hence, the tool provided a method to reduce the cost of creating a performance model and also to provide consistency between the design and the performance models of service-oriented systems.

Huang et al. [12] presented a procedure to create system models and introduce them automatically to simulation languages with the motivation of providing means to formalize the system modeling phase. SysML was used to model a typical flow shop and two types of models were developed: domain meta-model and analysis meta-model. The domain meta-model included Block Definition Diagrams (BDDs) and Internal Block Diagrams (IBDs), where blocks were arrival process, buffer, machine, workstation and the flow shop system. The analysis meta-model included a simulation model and a queuing model to include the calculations for utilization, cycle time and work-in-process. Simulation model was created with BDD or IBDs, whereas queuing model was created by BDDs or Parametric Diagrams. Domain model was mapped to simulation analysis meta-model and queuing analysis meta-model through SysML inter-block relations, i.e. generalization and aggregation.

Mapping the domain meta-model to the analysis meta-model, the prerequisite of model transformation to simulation environment was achieved. Then combined model was exported as XMI file to be processed by Xpath (W3C 1999). Hence the required inputs to form the Access database were obtained. As the last step, a script was created within the simulation package by the simulation meta-model in order to parse the database for simulation or queuing models. Corresponding simulation object was created and by this way the flowshop in SysML is automatically transformed to a simulation model.

Liehr and Buchenrieder [13] defined a method to simulate the system, by an event-driven Extended Queuing Network (EQN) simulator. The method includes three phases: model validation, simulation and analysis. The proposed simulator works on the XML profile of the simulation model and XPath expressions are used.

Liehr and Buchenrieder [14] introduced a performance simulation method for Hardware / Software systems considering the contribution of performance prediction during development phase. The approach included system description conducted in UML MARTE (Modeling and Analysis of Real-Time and Embedded Systems) profile, where the functionality was provided by an Activity Diagram, the hardware by Composite Structure Diagram and the mapping of the architectural components to the functionality by Allocation Diagrams. In order to obtain the simulation model, a list which included the hardware components contributing to the system functionality was compiled. The resulting list led to an EQN, which could be used for computer system and communication network simulations as stated by Liehr and Buchenrieder [13]. The behavior of the system was then mapped to the EQN, using Activity Diagram of the system model. The outcome of the study was an EQN model, ready to be simulated on an EQN simulator.

Johnson et al. [15] combined SysML's modeling capabilities with Modelica's simulation features to model continuous dynamics of systems. The study focused on SysML Parametric Diagrams, which could impose mathematical constraints among system properties. Embedded Plus and OpenModelica were the modeling environments for SysML and Modelica, respectively. The transformations between the two types of models were based on triple graph grammars (TGGs), where the source and target languages were defined as graphs. Mapping between the two languages was then achieved by applying graph transformation rules to a third graph. The approach suited well to continuous dynamics modeling.

Nikolaidou et al. [16] proposed a Discrete Event Simulation Specification (DEVS) SysML profile for graphical representation of DEVS models. In the profile, DEVS simulation model was described by BDDs and the interconnections by IBDs. Behavior of the model was represented by Activity Diagram, State Machine Diagram, Parametric Diagram and a constraint BDD. SysML model in MagicDraw was transferred to DEVS Modeling Language (DEVSML). However, code generation in DEVSML was not finished by this study.

Wang and Dagli [17] presented a method to transfer SysML models of discrete event systems to Colored Petri Nets (CPNs) in order to execute and refine the system architecture while verifying the system behavior. SysML was regarded as lacking execution capabilities and CPN as appropriate for model execution. However, due to CPN's poor static architecture description capability, it was not preferred as the architectural interface. The study focused on interactive behavior of system components and mainly considered SysML Sequence Diagrams. SysML diagram elements were mapped to the elements of a CPN model. It should be noted that additional CPN constructs were used for simulation and performance analysis in CPN.

Nikolaidou et al. [18] presented SysML as the modeling basis from systems engineering point of view and used Discrete Event System Specification (DEVS) framework for performance simulation purposes. Main motivation arose from the similarities between DEVS and SysML (i.e. object-oriented methodology) and ease of automatic code generation once the simulation capabilities were embedded into the SysML model. Hence, a DEVS profile for SysML was proposed.

DEVS profile was to be used in order to achieve the following:

- While structure of the system was defined by BDD and IBDs, DEVS-required information was to be included within these diagrams,
- Certain blocks were to be allocated as DEVS Simulation SysML Diagrams to define system behavior via DEVS functions, State Machine Diagram and Activity Diagram were used.
- Environment for the experiment was to be defined.
- DEVS simulation code was to be generated using the SysML diagrams.

The proposed profile was implemented in Magic Draw, a UML-modeling tool which supports SysML profile. The code generation was achieved by using SysML XMI output, converting it to DEVSXML format and transforming DEVSXML to the DEVS code, ready to be simulated by a DEVS simulator.

Although SysML model is constrained by DEVS formalism, systems engineering capabilities are increased with the help of simulation.

Schönherr and Rose [19] introduced a method to model a production system in SysML and transfer the model to a simulation environment. Activity Diagrams were considered as appropriate to represent related behavior. For transformation, a two-level method was used. In the first level, a parser was run on the exported XML file and eliminated the unnecessary parts. Then a "translator plug-in" was used to convert the data into the format required by the specific simulator. The advantage of this study was that it was generic and could be modified to fit different simulators. SysML modeling tool was Magic Draw, the two alternative simulators used were AnyLogic and Simcron.

McGinnis and Ustun [20] developed a method to create a conceptual model for the system to be simulated and to transform this conceptual model to a model in a simulation language. SysML was used to include model-driven architecture approach while developing a domain specific language for conceptual model creation. The target simulation software was Arena. The transformation process was initiated with exporting the SysML models as XMI files. The XMI files were subject to a series of transformations to be converted to Microsoft Access, which provides an interface to Arena. ATLAS Transformation Language was used to obtain the final XMI file, which was imported to Access. The transformation was completed by importing this Access file to Arena.

The methodology provided by McGinnis and Ustun [20] included the conceptual model being developed in SysML, which is standard and provides ease of accessibility to the customer. The reference model for SysML was the standard flow shop model, which included two workstations and within each workstation three identical machines in parallel. The final Arena model was composed of Process modules.

A summary of the studies given in this section is provided in Table 2.1. Studies in literature indicate that tools, which use UML/SysML facilitate a more structured way of modeling systems, providing a good user interface in a standardized language and reflecting object-oriented decomposition. However, it is a common requirement to simulate the modeled system in order to observe its performance before putting the system into operation. Among the several simulation environments used in the studies, Arena is regarded as appropriate in our study, due to its well-known import/export interfaces and simulation capabilities. Moreover, activity diagrams are preferred during modeling the system's process in order to describe the flow of activities and also for practical mapping to the simulation environment.

Table 2.1 Model Transformation Studies

Ref.	Modeling Language	Modeling Environment	Simulation Environment	Transformation Method	Transformed Diagrams
[10]	UML	N/A	Arena	SIMAN code	Use Case Diagram, Interaction diagrams (both sequence diagram and collaboration diagram), Class diagrams
[11]	UML	Eclipse-based Rational Software Modeler	HyPerformix Workbench	ATLAS Transformation Language	Use Case Diagram, Activity Diagram, Deployment Diagram
[12]	SysML	Embedded Plus Engineering's SysML toolkit for the Rational Software Delivery Platform	eM-Plant	Xpath	Block Definition Diagrams, Internal Block Diagrams, Parametric Diagrams
[14]	UML	N/A	Extended Queuing Networks (EQN)	Xpath	Activity Diagram, Composite Structure Diagram, Allocation Diagrams

Table 2.1 Model Transformation Studies (Continued)

Ref.	Modeling Language	Modeling Environment	Simulation Environment	Transformation Method	Transformed Diagrams
[15]	SysML	Embedded Plus	Modelica	Triple Graph Grammars	Parametric Diagrams
[16]	SysML	MagicDraw	N/A	XML	Block Definition Diagrams, Internal Block Diagrams, Activity Diagram, State Machine Diagram, Parametric Diagrams
[17]	SysML	N/A	N/A	N/A	Sequence Diagrams
[18]	SysML	MagicDraw	DEVS Simulator	DEVSXML	Block Definition Diagrams, Internal Block Diagrams, Activity Diagram, State Machine Diagram,
[19]	SysML	MagicDraw	AnyLogic, Simcron	XML	Activity Diagram
[20]	SysML	N/A	ARENA	ATLAS Transformation Language	N/A

CHAPTER 3

CONCEPTUAL MODEL FORMATION

In this chapter, the conceptual model for Systems Engineering Process is introduced. The concepts and references, from where the model is originated, are given in Section 3.1. The model is developed based on a two-phase survey conducted with the TAI engineers, reflecting their view of the Systems Engineering Process in a typical design project. The survey study and the survey results are provided in Section 3.2. Finally in Section 0, the conceptual model is presented.

3.1 CONCEPTUAL MODEL INITIALIZATION

In this section, we firstly define our system of concern from systems engineering point of view and then explain the basis for the conceptual model.

3.1.1 Systems Engineering Process as a System

Considering the system definitions provided in Section 2.1, the system of concern is identified as the Systems Engineering Process of a real-life design project including the post-design phases (i.e. production, testing, operation and maintenance). Although the proposed methodology is generic for a design project, design of an aerospace product was considered in order to assure a significant level of complexity. The system of concern is referred to as the "Systems Engineering Process" throughout the thesis.

INCOSE [1] defines a system element (subsystem) as "a major product, service or facility of the system". A similar definition is included in MIL-STD-499B [2], where the definition of subsystem is given as "a grouping of items satisfying a logical group of functions within a particular system". Setting the system as Systems Engineering Process, systems engineering activities are system elements or subsystems. A third level is also included for subactivities. Therefore, the system hierarchy to be reflected by the conceptual model is framed as given by Figure 3.1.

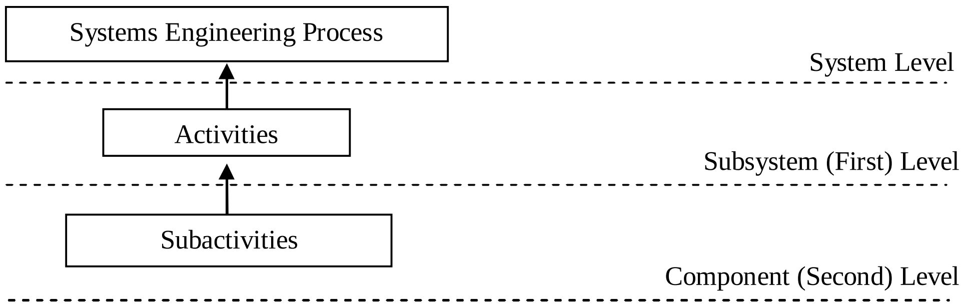


Figure 3.1 System Hierarchy

3.1.2 Conceptual Model Basis

Although there is a common understanding of systems engineering concept, the definitions of systems engineering activities differ among different references as given in Section 2.1. One reason might be that the allocation of systems engineering activities to the phases of a system's life cycle depends on the scope and complexity of the project [1]. Moreover, systems engineering process is iterative by nature and certain activities might need to be run in parallel [1]. Therefore, Systems Engineering Process activities are based on a common understanding but should be tailored for the project domain and scope.

In this thesis study, two well-known Systems Engineering references formed the basis of the method to identify the subsystems and components of the conceptual model. These are:

1. Technical Processes defined in INCOSE Systems Engineering Handbook [1].
2. Systems Engineering Processes given in “Fundamentals of Modern Systems Engineering” short course of Georgia Tech [5].

As introduced in Section 2.1, INCOSE [1] groups system life cycle processes as: Project Processes, Technical Processes, Organizational Project-Enabling Processes and Agreement Processes. These processes are considered to be applicable to all stages of life cycle as appropriate to the nature of the project [1]. Considering our system of concern and our objective of modeling and simulation of the system to observe its performance in terms of resource utilization and duration, the Technical Processes are considered as the performance identifiers. Although the rest of the process groups (especially the project processes) contributes to the whole process, they are not regarded as the key groups and assumed to run in parallel with the technical processes.

Georgia Tech [5] categorizes systems engineering processes in a very similar approach to INCOSE [1] as: Project Processes, Technical Processes, Enterprise Processes and Agreement Processes. It is noted that these processes are used where needed during the life cycle. The set of systems engineering processes, which reflect the technical perspective, contributes to our conceptual model.

The technical activities provided by INCOSE [1] and Georgia Tech [5] established a basis to identify the system elements and system components, which then formed the conceptual model, as detailed in Section 3.2 and Section 0.

3.2 THE SURVEY STUDY

A two-phase survey study was conducted with the Systems Engineering team members, who work in Helicopter Group in Turkish Aerospace Industries, Inc. Ten systems engineers participated in each phase of the survey, where seven of them participated in both phases.

3.2.1 Survey Study – Phase 1

The objectives of Phase 1 of the survey were:

- To identify the first level systems engineering activities, and
- To obtain a precedence diagram of the identified activities.

A questionnaire was given to each respondent and before he or she filled out the questionnaire, an interview was conducted to briefly describe the aim of the survey and content of the questionnaire. The questionnaire of Survey Study – Phase 1 is given in Appendix A.1.

It was stated in the first part of the questionnaire that the Systems Engineering Process of concern was a real-life design project conducted in the organization of the respondent. Since the organization was an aerospace company for all respondents, the preferred complexity level for the system was inherently satisfied. The two references were not openly shared with the respondents but mentioned as Reference 1 and Reference 2, where Reference 1 and Reference 2 represented INCOSE [1] and Georgia Tech [5], respectively.

The questionnaire was composed of two parts. In Part 1 of the questionnaire, a table including the first level activities in two references, which were described in Section 3.1.2, were provided to the respondents. In each row of the table, the first column included the activity code, the second column included corresponding Reference 1 activity name and purpose, and the third column included corresponding Reference 2 activity name and purpose. The fourth column was left blank for the respondent to put a check symbol, where he or she thinks related activity should be included within the systems engineering process. Therefore, the table included a row for each distinct activity.

A sample row, which indicates an activity included in only one reference (Reference 1 only for this activity) is given in Table 3.1. A sample row, which indicates an activity included in both references (Reference 1 and Reference 2) is given in Table 3.2.

Table 3.1 Example Activity 1

Activity Code	Reference 1 Activity Name and Purpose	Reference 2 Activity Name and Purpose	Included or Not
SRD	Stakeholder Requirements Definition *Define the requirements for a system that can provide the services needed by users and other stakeholders in a defined environment*		

Table 3.2 Example Activity 2

Activity Code	Reference 1 Activity Name and Purpose	Reference 2 Activity Name and Purpose	Included or Not
RA	Requirements Analysis *Transform the stakeholder, requirement-driven view of desired services into a technical view of a required product that could deliver those services*	Requirements Analysis *Define system customers, determine requirements from desirements, validate system requirements with system customers*	

In Part 2 of the questionnaire, the respondent was asked to provide a precedence diagram for the activities which he or she stated as to be included in the systems engineering process in Part 1. Therefore Part 2 was to be compliant with Part 1 for each respondent.

One important information included in the questionnaire was related with the respondents' experience in systems engineering (in years). This data was then converted to a weight for each respondent and used as an input for the final conceptual model.

First level activity diagrams from 10 respondents were obtained at the end of Survey Study – Phase 1. The method followed to evaluate the outcomes of Phase 1 survey is described in the next section.

3.2.2 Survey Study – Phase 1 Results

Phase 1 survey outcomes were evaluated in order to obtain the following:

- Activities, which would be included in the final first level activity network.
- Final first level activity network with precedence relations.

Evaluation of survey results is described in two parts in accordance with the objectives indicated above. Firstly the activity selection for the first level activity network is detailed and then the precedence relations definition method is provided.

Activity selection process is detailed in the following parts.

1. The information concerning whether an activity was selected by a respondent or not is given in Table 3.3 in accordance with the following definitions.

   i: $Activities\ SRD, MA, RA, BM, FA, TS, AA, SS, AD, IMP, INT, VER,$
   $TRANS, VAL, OP, MAINT, DIS, SEP$

   j: $Respondents\ 1, 2, \ldots, 10$

   $$A_{ij} = \begin{cases} 1, if\ activity\ i\ is\ selected\ by\ respondent\ j \\ 0, otherwise \end{cases}$$

Table 3.3 Activity Selection in Phase 1

		Respondent Reference (j)									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Activity Code (i):	**SRD**	0	0	1	0	0	1	1	1	0	1
	MA	1	1	1	0	1	1	0	1	1	0
	RA	1	1	1	1	1	1	1	1	1	1
	BM	0	0	0	0	0	0	1	0	1	1
	FA	1	1	1	1	1	1	1	1	1	0
	TS	0	0	1	0	1	1	1	0	0	0
	AA	0	0	1	0	0	1	0	0	1	0
	SS	0	1	1	0	1	1	0	1	1	0
	AD	1	1	0	1	0	0	1	1	1	1
	IMP	0	0	0	0	0	0	0	0	0	0
	INT	1	1	1	1	1	1	1	1	1	1
	VER	1	1	1	1	1	1	1	1	1	1
	TRANS	0	0	0	0	0	0	0	0	0	1
	VAL	1	1	1	1	1	1	1	0	1	1
	OP	0	1	1	0	0	1	1	0	0	1
	MAINT	1	0	1	1	0	1	1	0	0	1
	DIS	1	0	1	1	0	1	1	0	0	1
	SEP	1	1	0	1	1	1	1	1	1	1

2. Experience of each respondent is given in Table 3.4 in accordance with the following definition.

$$E_j: Experience\ of\ respondent\ j\ in\ years$$

3. Weight of each respondent is calculated in accordance with the formula below. Results are included in Table 3.4.

$$W_j = \frac{E_j}{\sum E_j}$$

Table 3.4 Respondent Weights in Phase 1

Respondent Reference (j)	SysEng Experience (Ej)	Weight (Wj)
1	1	0.03
2	2	0.06
3	3.5	0.10
4	4	0.12
5	1	0.03
6	2.5	0.07
7	3	0.09
8	5	0.15
9	3	0.09
10	9	0.26
TOTAL:	**34**	1.00

4. Weighted Activity Score of each activity is calculated in accordance with the formula below. Results are given in Table 3.5.

$$AS_i = \sum_j A_{ij} \qquad WAS_i = \sum_j W_j A_{ij}$$

Table 3.5 Activity Scores in Phase 1

Activity Code:	Activity Score (ASi):	Weighted Activity Score (WASi):
SRD	5	0.68
MA	7	0.53
RA	10	1.00
BM	3	0.44
FA	9	0.74
TS	4	0.29
AA	3	0.26
SS	6	0.50
AD	7	0.79
IMP	0	0.00
INT	10	1.00
VER	10	1.00
TRANS	1	0.26
VAL	9	0.85
OP	5	0.59
MAINT	6	0.68
DIS	6	0.68
SEP	9	0.90

Activities are selected according to the following criterion.

If $WAS_i \geq 0.50$, activity i is included in the final first level network

If $WAS_i < 0.50$, activity i is not included in the final first level network

According to this criterion, 13 of the 18 activities are selected to be included in the conceptual model. Weighted activity scores of selected activities are shaded in the last column of Table 3.5.

At the end of Step 5, activities to be included in the final first level network are identified as: SRD, MA, RA, FA, SS, AD, INT, VER, VAL, OP, MAINT, DIS and SEP. Remaining activities are omitted and are not considered in following parts of the survey evaluation.

Precedence relations among selected activities are defined as detailed in the following steps.

5. For each activity, candidate predecessors (all remaining activities other than the activity itself) are listed. The information regarding whether or not a respondent selected a candidate activity as a predecessor for an activity is given in Table 3.6, using activity AD as an example. Following definitions apply.

   i: $Activities\ SRD, MA, RA, FA, SS, AD, INT, VER,$

   $VAL, OP, MAINT, DIS, SEP$

   k: $Activities\ other\ than\ activity\ i$

   j: $Respondents\ 1, 2, \ldots, 10$

$$P_{ikj} = \begin{cases} 1, if\ activity\ k\ is\ selected\ as\ a\ predecessor \\ \quad of\ activity\ i\ by\ respondent\ j \\ 0, otherwise \end{cases}$$

Complete Table B.1 for all the activities is given in Appendix B.

Table 3.6 Predecessor Selection Example in Phase 1

Activity (i)	Candidate Predecessors for Activity i (k):	Respondent Reference (j):									
		1	2	3	4	5	6	7	8	9	10
AD	**SRD**	0	0	0	0	0	0	**1**	**1**	0	**1**
	MA	**1**	**1**	0	0	0	0	0	**1**	**1**	0
	RA	**1**	**1**	0	**1**	0	0	**1**	**1**	**1**	**1**
	FA	**1**	**1**	0	**1**	0	0	**1**	**1**	0	0
	SS	0	**1**	0	0	0	0	0	0	0	0
	INT	0	0	0	0	0	0	0	0	0	0
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0

Table 3.6 Predecessor Selection Example in Phase 1 (Continued)

Activity (i)	Candidate Predecessors for Activity i (k):	Respondent Reference (j):									
		1	2	3	4	5	6	7	8	9	10
AD	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	**1**	0	0	0	0	0	0	**1**	**1**	0

6. Weighted Predecessor Score of each candidate predecessor for each activity is calculated in accordance with the formula below. Results are given in Table 3.7 for activity AD as an example.

$$WPS_{ik} = \sum_{j} W_j P_{ikj}$$

Complete Table B.2 for all the activities is given in Appendix B.

Table 3.7 Predecessor Scores Example in Phase 1

Activity (i)	Candidate Predecessors for Activity i (k):	Weighted Predecessor Score (WPSik)	WASi	WPSik / WASi
AD	SRD	0.50	0.79	0.63
	MA	0.32	0.79	0.41
	RA	0.79	0.79	1.00
	FA	0.44	0.79	0.56
	SS	0.06	0.79	0.07
	INT	0.00	0.79	0.00
	VER	0.00	0.79	0.00
	VAL	0.00	0.79	0.00
	OP	0.00	0.79	0.00
	MAINT	0.00	0.79	0.00
	DIS	0.00	0.79	0.00
	SEP	0.26	0.79	0.33

7. Predecessors are selected in accordance with the following criterion.

   If $WPS_{ik} / WAS_i \geq 0.45$, activity k is included as a predecessor of activity i in the final first level network

   If $WPS_{ik} / WAS_i < 0.45$, activity k is not included as a predecessor of activity i in the final first level network

   Here, the selection threshold is taken as 0.45 because it represents a natural breakpoint. Weighted predecessor scores of selected predecessors of sample activity AD are shaded in Table 3.7. Complete results for all activities can be found in Table B.2 in Appendix B.

   In order to derive the precedence network out of the selected predecessors of each activity certain assumptions are made. As indicated in Table B.2 of Appendix B, SEP is selected as a predecessor of MA, SS and DIS but not of any other activities, although it is selected to be included in the process by 10 out of the 13 respondents. Since SEP is a planning activity, which is subject to iterations during the whole systems engineering process, it is assumed to be a predecessor of only DIS in the final network.

   MA is selected as a predecessor of FA, SS, INT and VER. However, FA, INT and VER are predecessors of VAL, MAINT, OP, DIS. Therefore, considering the content of MA (mission analysis which is to be conducted at the earlier phases of the process), MA is placed prior to FA in the final network. A similar case exists for SS, being a predecessor of INT and VER. Since INT and VER are predecessors of VAL, MAINT, OP and DIS, SS is placed prior to INT in the final network. In fact this situation might be expected for MA and SS, since their weighted average activity scores are 0.53 and 0.50, respectively and they are the lowest scored activities among the activities included in the process.

At the end of Step 8, a precedence network for the first level systems engineering activities is obtained. This network identifies the precedence relations among the subsystems of a system. Here, the system is the Systems Engineering Process for a design project, and subsystems correspond to the first level (main) activities of the Systems Engineering Process. The final first level activity network of our conceptual model is given in Figure 3.2, after presenting the second phase of the survey.

3.2.3 Survey Study – Phase 2

At the end of Phase 1, the precedence network for the first level activities is obtained. Phase 2 is to be built upon this first level network. Therefore, the objectives of Phase 2 of the survey are:

- To identify the subactivities, which are the second level systems engineering activities, and
- To obtain a precedence diagram of the subactivities for each activity.

Among the 13 activities of the first level precedence network, only RA, INT and VER are included in both Reference 1 and Reference 2. Therefore, the subactivities for the remaining 10 activities are directly taken as they are defined in the respective reference (Reference 1 or Reference 2). Subactivities for the three activities, which are common in both references, are to be evaluated in Phase 2.

In Phase 2, a questionnaire was given to each respondent similar to Phase 1 and before he or she filled out the questionnaire, an interview was conducted to briefly describe the aim of the survey and content of the questionnaire. The questionnaire of Survey Study – Phase 2 is given in Appendix A.2.

Phase 2 questionnaire also included two parts. In Part 1, a table was provided to the respondents. Each of the three common activities had a row in the table. The first column included the activity code and name, the second column included corresponding Reference 1 subactivities and the third column included corresponding Reference 2 subactivities. The fourth column was left blank for the respondent to note the reference which he or she thought that includes the most appropriate subactivities for the related activity. Hence, each respondent specified a subactivity set for each of the three common activities. A row from the table is given in Table 3.8 as an example.

Table 3.8 Example Activity 3

Activity	Reference 1 Subactivities	Reference 2 Subactivities	Selected Reference
RA Requirements Analysis	**1.** Define the System Requirements **2.** Analyze and Maintain the System Requirements	**1.** Define System Customers **2.** Determine Requirements from "desirements" **3.** Validate system requirements with system customers	

The number of subactivities is small for all activities. Therefore, once a reference is selected for each of the three common activities, all given subactivities are included in the second level networks of all activities.

In Part 2 of Survey Study – Phase 2, the respondent was asked to provide a precedence diagram for each activity, using the given subactivities. For the three activities, which were common in both references, the subactivities for the selected reference were to be used. Therefore, Part 2 was to be compliant with Part 1 for each respondent.

Respondents' experience in systems engineering (in years) was also collected in Part 2, similar to Part 1. This data was then converted to a weight for each respondent and used as an input to the final conceptual model.

Ten sets of second level activity diagrams were obtained at the end of Survey Study – Phase 2. The method which was followed to evaluate the outcomes of Phase 2 survey is described in the next section.

3.2.4 Survey Study – Phase 2 Results

Phase 2 survey outcomes were evaluated in order to obtain the following:

- The reference (Reference 1 or Reference 2) to be used for each of the three activities (RA, INT and VER), which are common in both references.
  (The result of the reference selection would provide the second level activities for these three activities.)
- Final second level activity network for each first level activity.

Evaluation process is described in two parts in accordance with the objectives indicated above. Firstly, a reference is selected for each of the activities RA, INT and VER. Then, the precedence diagrams are obtained for each first level activity.

Reference selection process is detailed below.

1. The information of whether Reference 1 or Reference 2 is selected by a respondent is given in Table 3.9 in accordance with the following definitions.
   i: $Activities\ RA, INT, VER$
   l: $References\ 1, 2$
   j: $Respondents\ 1, 2, \ldots .10$
   $$R_{ilj} = \begin{cases} 1, if\ reference\ l\ is\ selected\ for\ activity\ i\ by\ respondent\ j \\ 0, otherwise \end{cases}$$

Table 3.9 Activity Selection in Phase 2

			Respondent Reference (j):									
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Activities (i)	**RA**	**Reference 1**	1	1	1	0	1	0	0	1	1	0
		Reference 2	0	0	0	1	0	1	1	0	0	1
	INT	**Reference 1**	1	0	1	1	1	1	1	1	1	1
		Reference 2	0	1	0	0	0	0	0	0	0	0
	VER	**Reference 1**	1	1	1	1	1	1	1	1	1	1
		Reference 2	0	0	0	0	0	0	0	0	0	0

2. Experience of each respondent is included in Table 3.10 in accordance with the following definition.

$$E_j: Experience\ of\ respondent\ j\ in\ years$$

3. Weight of each respondent is calculated in accordance with the formula below. Results are included in Table 3.10.

$$W_j = \frac{E_j}{\sum E_j}$$

Table 3.10 Respondent Weights in Phase 2

Respondent Reference (j)	SysEng Experience (Ej)	Weight (Wj)
1	1	0.03
2	1	0.03
3	5	0.13
4	8	0.21
5	1	0.03
6	3	0.08
7	3	0.08
8	5	0.13
9	3	0.08
10	9	0.23
TOTAL:	**39**	1.00

4. Weighted Reference Score of each reference for each activity is calculated in accordance with the formula below and given in Table 3.11.

$$RS_{il} = \sum_j R_{ilj} \qquad\qquad WRS_{il} = \sum_j W_j R_{ilj}$$

Table 3.11 Reference Scores in Phase 2

Activity Code:	Reference:	Reference Score (RSil):	Weighted Reference Score (WRSil):
RA	Reference 1	6	0.41
	Reference 2	4	0.59
INT	Reference 1	9	0.97
	Reference 2	1	0.03
VER	Reference 1	10	1.00
	Reference 2	0	0.00

5. For each of the three activities, the reference having the higher WRS_{il} score is selected, as indicated by shaded cells in Table 3.11.

At the end of Step 5, Reference 2, Reference 1 and Reference 1 are selected for activities RA, INT and VER, respectively.

Precedence relations among the second level activities are defined as follows.

6. Weighted Activity Scores are needed for precedence diagrams of each activity. Since the second level activities other than those of RA, INT and VER are already included in the network at the beginning of Survey Phase 2, corresponding weighted activity scores are taken as 1.

   For the second level activities of RA, INT and VER, weighted activity scores are the same as the WRS_{il} values where l is the selected reference, as indicated in shaded cells in Table 3.11.

7. Predecessor selection is conducted in the same manner as described in Survey Phase 1. The information concerning whether or not a respondent selected a candidate second level activity as a predecessor for another second level activity is given in Table 3.12 for sample activity AD. The following definitions are used.

   i: $Activities\ SRD, MA, RA, FA, SS, AD, INT, VER,$

   $VAL, OP, MAINT, DIS, SEP$

   n: $Second\ level\ activities\ of\ each\ activity\ i$

k: *Second level activities other than n for each activity i*

j: *Respondents* $1, 2, \ldots .10$

$$P_{inkj} = \begin{cases} 1, \text{if second level activity } k \text{ of activity } i \text{ is selected as} \\ \quad \text{a predecessor of second level activity} \\ \quad n \text{ of activity } i \text{by respondent } j \\ 0, \text{otherwise} \end{cases}$$

Hence, there is a distinct predecessor matrix for each activity i.

Complete results are presented in Table B.3 in Appendix B.

Table 3.12 Predecessor Selection Example in Phase 2

			Respondent Reference (j):									
Activity (i)	**Subactivity (n)**	**Candidate Predecessors for Each Subactivity (k)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
AD	**AD1**	**AD2**	0	0	0	0	0	0	0	0	0	0
		AD3	0	0	0	0	0	0	0	0	0	0
	AD2	**AD1**	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	0	**1**
		AD3	0	0	0	0	0	0	0	0	0	0
	AD3	**AD1**	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0
		AD2	**1**	0	0	**1**	**1**	0	0	**1**	**1**	0

8. Weighted Predecessor Score of each candidate predecessor for each second level activity is calculated in accordance with the formula below.

$$WPS_{ink} = \sum_{j} W_j P_{inkj}$$

Results for sample activity AD are in Table 3.13 and complete results are in Table B.4.

8. Predecessors are selected in accordance with the following criterion.

   If $WPS_{ink} / WAS_{in} \geq 0.50$, second level activity k is included as a predecessor of second level activity n for activity i in the final second level network

   If $WPS_{ink} / WAS_{in} < 0.50$, second level activity k was not included as a predecessor of second level activity n for activity i in the final second level network

   Results for sample activity AD are in Table 3.13 and the complete results are included in Table B.4 in Appendix B.

Table 3.13 Predecessor Scores Example in Phase 2

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
AD	AD1	AD2	0,00	1,00	0,00
		AD3	0,00	1,00	0,00
	AD2	AD1	0,92	1,00	0,92
		AD3	0,00	1,00	0,00
	AD3	AD1	0,77	1,00	0,77
		AD2	0,46	1,00	0,46

At the end of Step 9, a precedence network for the second level activities of each of the first level systems engineering activities is obtained. When these second level networks are combined, a more detailed overall activity network is obtained, indicating the precedence relations among both subsystems and components of our system.

3.3 THE CONCEPTUAL MODEL

Based on the technical processes defined in INCOSE [1] and systems engineering processes in Georgia Tech [5], a two-phase survey was conducted, with 10 systems engineers in each phase. The resultant precedence diagrams reflect the two levels of our system:

- Subsystem level, as obtained by the first level activity network
- Component level, as obtained by the second level activity network

Our conceptual model is given in Figure 3.2 for the first level activity network.

The conceptual model for the second level activity networks is summarized in Figures C.1 through C.13 in Appendix C. When these networks are combined a more detailed second level network can be obtained. Part of the second level network including activities FA, SS and AD is given in Figure 3.3 as an example.

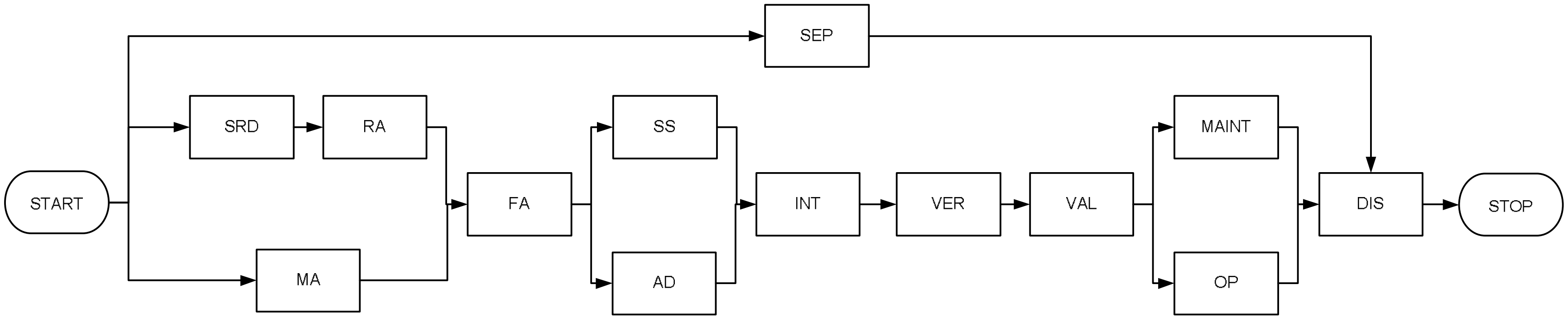


Figure 3.2 Final First Level Activity Network of the Conceptual Model

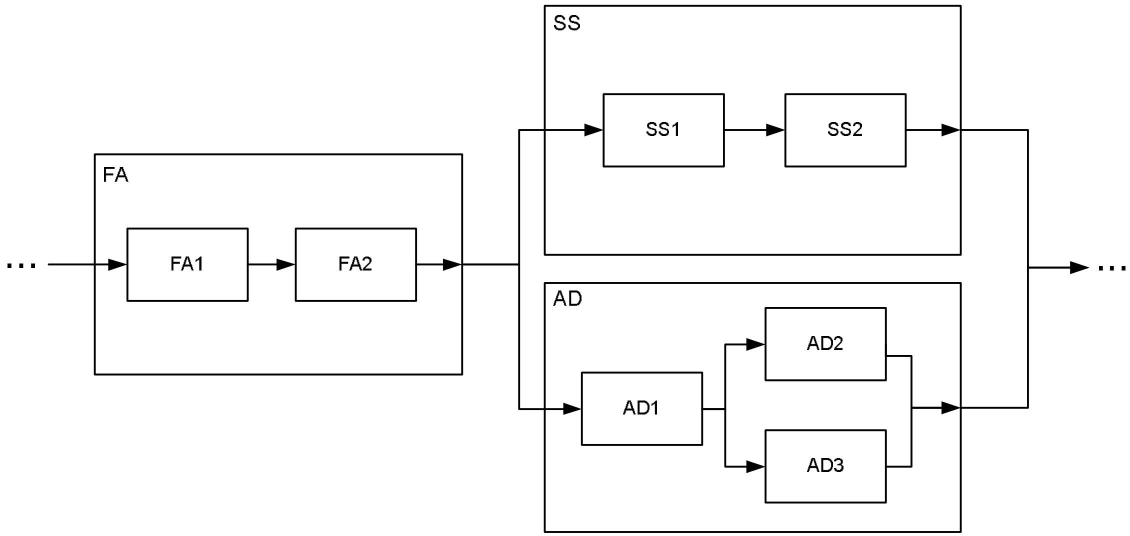


Figure 3.3 Partial Second Level Activity Network of the Conceptual Model

CHAPTER 4

MODELING OF SYSTEMS ENGINEERING PROCESS IN SYSML

In this chapter, implementation of the Conceptual Model in SysML is described. In Section 4.1, the SysML model is defined in structural and behavioral aspects and in Section 4.2, model properties and simulation input parameters are introduced.

4.1 MODELING STRUCTURE AND BEHAVIOR OF THE SYSTEM

Based on the Conceptual Model, which was defined in Chapter 3, Systems Engineering Process is modeled using the modeling language SysML in the modeling environment IBM Rational Rhapsody. SysML diagrams provide means to model the system in terms of its structure, behavior and requirements [9] and facilitates the reflection of the system to any level of abstraction [3], as introduced in Chapter 2.

This study focuses on modeling the structure of the system with block definition diagrams and the behavior of the system with activity diagrams. Since our system of concern is not a tangible product made of hardware and software, but a process instead, each system block has its corresponding activity. Therefore, the block definition diagrams and activity diagrams are interrelated.

4.1.1 Modeling Structure by Block Definition Diagrams

The Conceptual Model includes two levels of activity networks. Thus, a two-level hierarchy is to be considered while constructing the system structure. The first level corresponds to Systems Engineering Process structure and the second level corresponds to the structure of each first level systems engineering activity

.

Modeling these two levels enable us to represent the system and subsystems by structural aspects.

Defining the system as a process, main system units (blocks) indicate process parts (activities). “Part Association” [9] is used in order to describe the composition relation among the system block (Systems Engineering Process) and the blocks representing the subsystems (first level systems engineering activities). Systems Engineering Process block definition diagram is given in Figure 4.1.

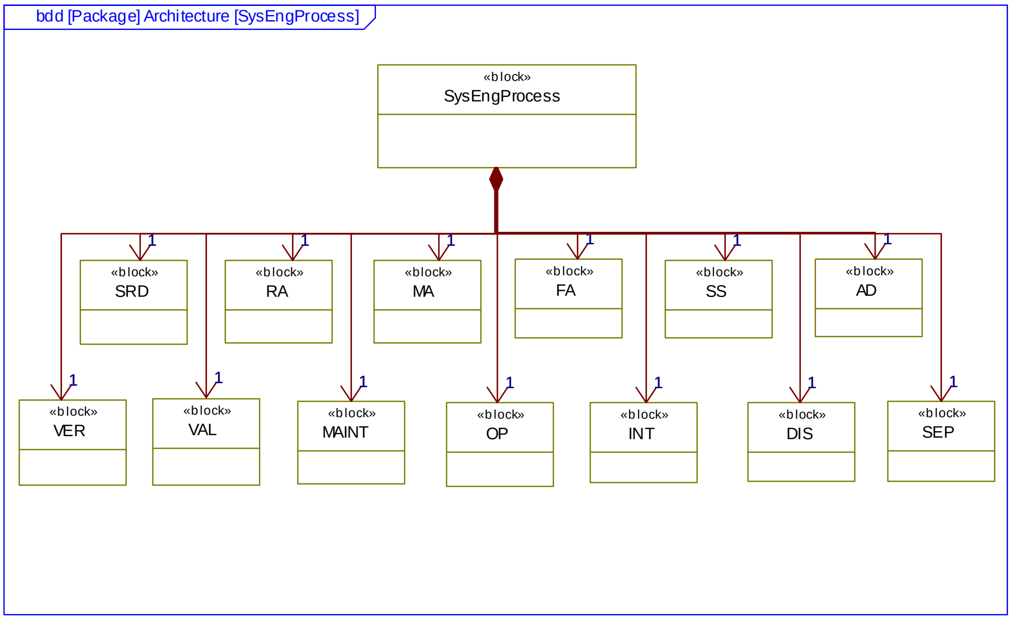


Figure 4.1 Systems Engineering Process Block Definition Diagram

Defining each subsystem as a process, subsystem units also indicate process parts (subactivities). Again “Part Association” [9] is used in order to describe the composition relation among a subsystem block and the blocks representing the components (second level systems engineering activities). Block definition diagram for sample activity AD is shown in Figure 4.2.

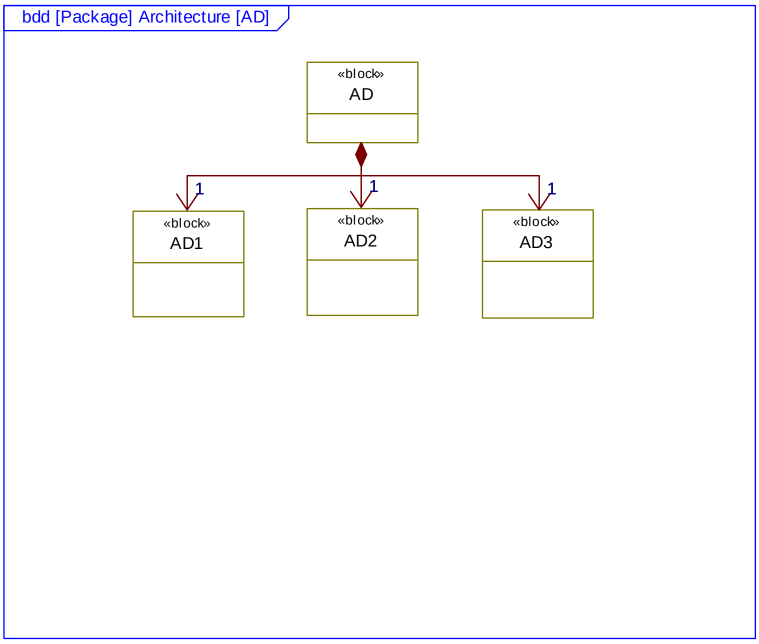


Figure 4.2 Architectural Design Block Definition Diagram

4.1.2 Modeling Behavior by Activity Diagrams

Although behavior of a system can be modeled in several ways in SysML, when a flow is to be defined as in the case of a process, an activity diagram is a good choice [3]. Hence, the behavior in Systems Engineering Process is modeled using activity diagrams. The Conceptual Model included two levels of activity networks, meaning two levels of flow. Firstly, Systems Engineering Process is modeled considering the flow of first level systems engineering activities. Then, each systems engineering activity is modeled considering the flow of second level systems engineering activities. Therefore, the behavior of the overall system is represented by activity diagrams.

Highest level behavior is reflected by the activity diagram of overall Systems Engineering Process. In this activity diagram, each first level systems engineering activity is indicated by a nested action called "Subactivity" in Rhapsody. Each first level systems engineering activity includes the relations between related second level activities.

Systems Engineering Process network structure, which includes parallel activities, is reflected by fork and join nodes. The flow of first level systems engineering activities within Systems Engineering Process is indicated by an activity diagram as given in Figure 4.3.

Second level behavior is represented by activity diagrams, each including subactivities of a first level systems engineering activity. In the activity diagram of a first level systems engineering activity, second level activities are indicated by actions. The network structure is again achieved by using fork and join nodes, where parallel activities are observed. The flow of second level systems engineering activities of sample activity AD is indicated in Figure 4.4.

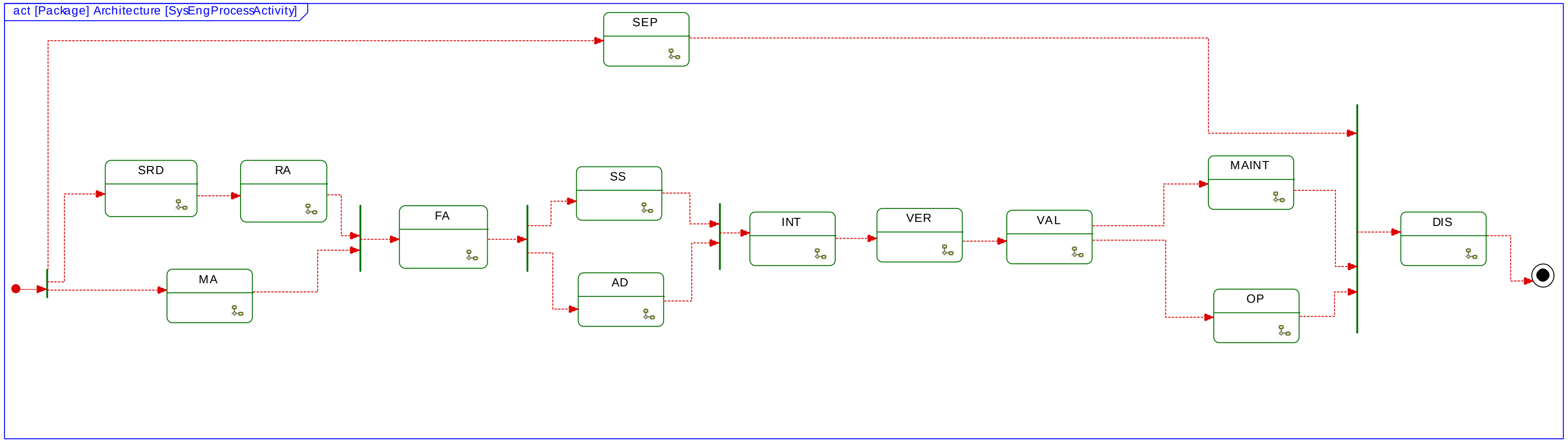


Figure 4.3 Systems Engineering Process Activity Diagram

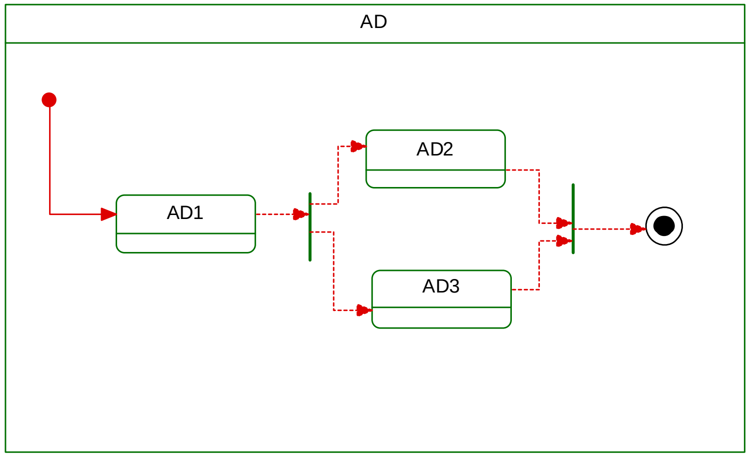


Figure 4.4 Architectural Design Activity Diagram

In addition to the activity diagrams, use case diagrams can also be used for modeling the behavior [9]. Use case of concern reflects the overall functionality of conducting systems engineering. The use case diagram for the systems engineering process is given in Figure 4.5. The actors Systems Engineer (SysEng), Subject Matter Expert (SME) and Project Manager (PM) represent the roles of the group of people who are using the system, and also who are being used by the system to achieve its intended purpose. These actors and their role in simulation will be explained further in the following section.

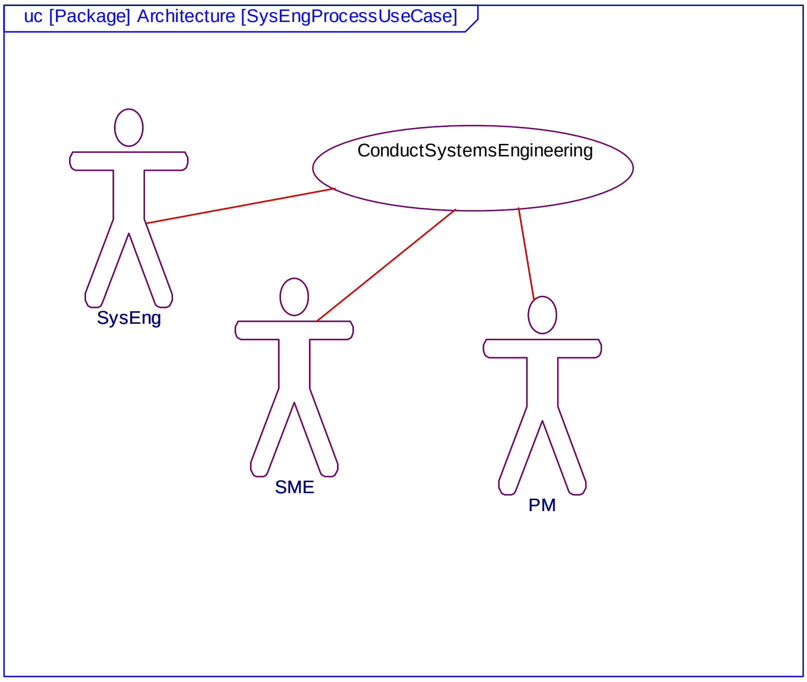


Figure 4.5 Systems Engineering Process Use Case Diagram

4.2 MANAGING MODEL PROPERTIES AND INPUT PARAMETERS

After describing the conceptual model implementation in SysML in Section 4.1, this section includes necessary properties of the final SysML model, before it can be transformed to ARENA simulation environment.

The proposed SysML model so far represents the structure of the system in terms of system hierarchy and the behavior in terms of precedence relations. However, a set of evaluation criteria is needed in order to build different system alternatives and compare them before setting a baseline to the model. Once the evaluation criteria (or performance measures) are determined, simulation can be conducted for system evaluation.

Value of a project, product or process can be improved by achieving a lower total life cycle cost (using less resource) and meeting schedule objectives, assuming that the project satisfies all its essential functions and requirements at required levels [1]. Similarly, timing and cost can be regarded as two of the indicators of project performance [21]. Assuming that our system-of-concern achieves its functionality when all activities in the process are completed, project duration and resource usage can be regarded as indicators of system's performance or value. In other words, project duration and resource usages form our evaluation criteria, according to which different system alternatives can be analyzed.

The abstraction level of the model requires that duration and resource requirements of second level systems engineering activities are the input parameters to be set for each system alternative. Duration is the time required for an activity to be completed in terms of days. Assuming resources other than labor do not differ among the system alternatives, resource types are defined as follows:

1. Project Manager (PM)
2. Systems Engineer (SysEng)
3. Subject Matter Expert (SME)

Descriptions of the resource types are given below.

Project Manager (PM): Although a PM can be regarded as the person responsible for planning, implementing and completing the project [21], due to his concentration on management tasks and limited communication with the disciplines, the holistic system view might be lost [3]. In this study, a PM is considered as the person who defines a high level roadmap for the project to achieve its success criteria, evaluates the effects of the technical risks to the management and revises the roadmap when required. Since our study assumes that the Project Processes defined in INCOSE [1] flow in parallel to the systems engineering process, Project Processes are not introduced within the scope of the study as distinct activities. PM's participation in the technical part of the systems engineering process is considered, where more than one PM can be allocated to a project, representing a project management team.

Systems Engineer (SysEng): SysEng is the connecting link between the disciplines in the project and is the system level architect [3]. In addition to these, SysEng is regarded in this study as the technical success enabler, considering the complete problem [1]. SysEng works close to PM [1], determines technical risks, and provides possible solutions.

Subject Matter Expert (SME): In this study, SME is considered as any person participating in the systems engineering activities but not a systems engineer or a project manager. SME can be a structural engineer, a test engineer, a technician working at the production line, etc. SME has a knowledge and/or experience in a particular discipline.

Considering the resource definitions above, the SysML model is updated to include the resource requirements and duration for every second level systems engineering activity as well as resource availabilities of the project. In Rhapsody, resource and duration information are entered in the description tab of related action as initial values, which can easily be adjusted later on. Resource availabilities are similarly added in the description tab of related actor.

Although the export interface is provided via XMI in Rhapsody, another method is followed in this study using the Table View and Table Layout properties. First a Table Layout is defined to include the actor and activity names in one column and the actor or activity descriptions (consisting of available resource values, duration and resource requirements) in the other . Then, a Table view is created to have the activities and actors in one column and corresponding descriptions in the second column. In the table, activity descriptions are included only for the second level systems engineering activities, as expected. An example for a part of the Table View with initial resource and duration values is given in Figure 4.6 Table View Example in Rhapsody.

Name	Description
SysEng	10
SME	30
PM	2
MA	
MA	
MA1	Duration:2 SysEng:2 SME:1 PM:1
MA2	Duration:3 SysEng:2 SME:1 PM:1
MA3	Duration:2 SysEng:2 SME:1 PM:0
RA	
RA	
RA3	Duration:3 SysEng:3 SME:1 PM:1
RA4	Duration:7 SysEng:4 SME:2 PM:0
RA5	Duration:5 SysEng:3 SME:2 PM:0

Figure 4.6 Table View Example in Rhapsody

With specification of duration and resource requirements for second level activities, implementation of the conceptual model in SysML is complete. The implementation includes the minimum set of input parameters necessary for transforming the model to an Arena simulation model.

CHAPTER 5

MODEL TRANSFORMATION FOR SIMULATION

In this chapter, transformation of the SysML model to the Arena simulation model is described. In Section 5.1, the base Arena model is introduced and in Section 0 transformation process is described.

5.1 BASE ARENA MODEL

In Chapter 4, a SysML model was created reflecting the conceptual model and including initial values of duration and resource requirements for each second level systems engineering activity. Within the SysML model, first and second level activity networks are the main parts and are kept as they are through the simulation and alternative analysis studies. The conceptual model also provides a basis for the simulation model, to which the system hierarchy and the flow of first and second level activities are direct inputs. In order to automate the model transformation, a base simulation model is created considering the conceptual model together with initial values of activity durations and resource requirements.

The base model includes Arena representation of the conceptual model. In the Experiment Frame, following elements are included:

1. Resources: SysEng, SME and PM
2. Queues: Queue1, Queue2, …, Queue25
3. Replicate
4. Tallies: Completion Time

In the Model Frame, following blocks and submodels are included:

1. Submodels: A submodel for each first level systems engineering activity
2. Blocks: Create, Duplicate, Queue, Seize, Delay, Release, Match and Dispose

Therefore, the Model Frame reflects the activity network of the conceptual model and the Experiment Frame defines resources, queues and replication length in order to complement the model content for simulation. Arena model view of the first level activity network is given in Figure 5.1.

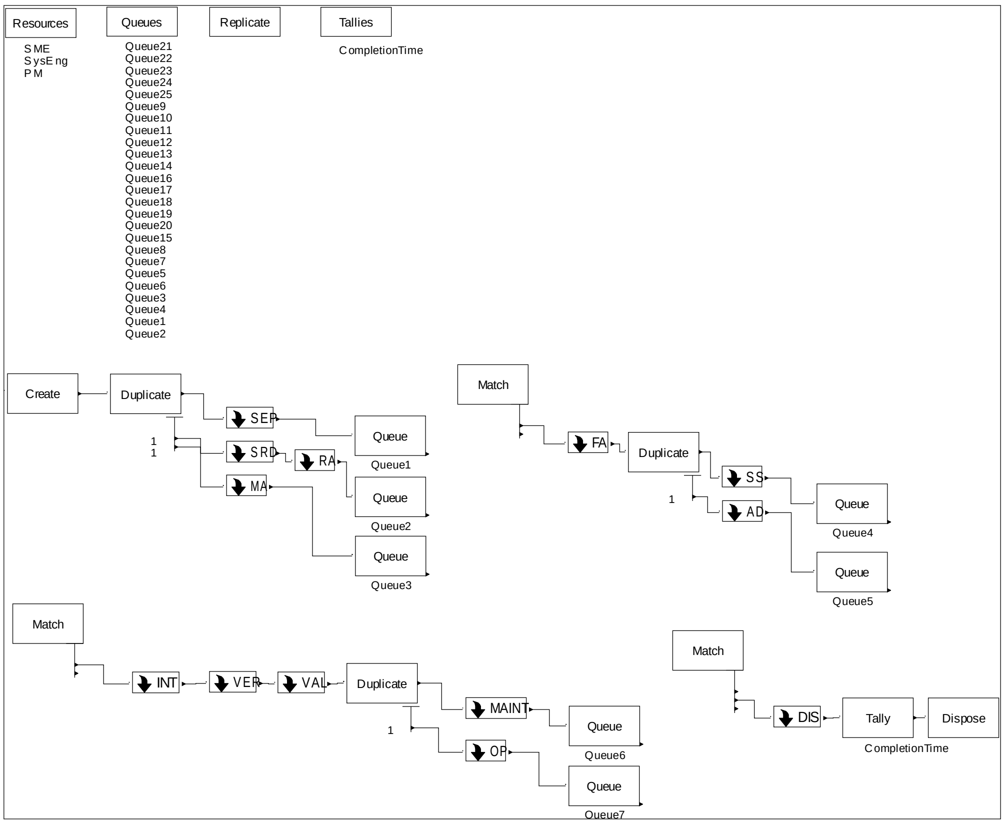


Figure 5.1 Arena Model View of the First Level Activity Network

In Figure 5.1, each of the 13 first level activities is represented by an Arena submodel. A Duplicate block is used after an activity if it has multiple successors. A Match block is used before an activity when it has multiple predecessors.

Each submodel contains related second level activity network. The second level activities included in a submodel are also submodels. The Arena model view of Submodel AD is given as an example in Figure 5.2.

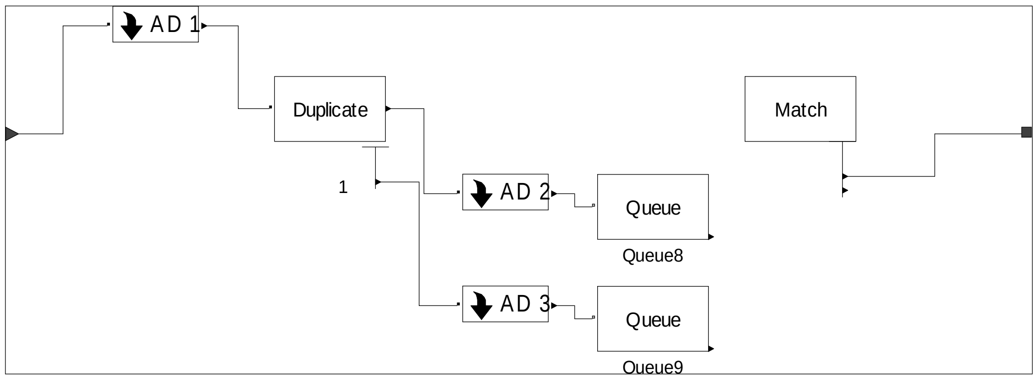


Figure 5.2 Arena Model View of Submodel AD

Within each submodel of a second level systems engineering activity, there is the standard Seize-Delay-Release blocks form. This third level of Arena model provides the necessary simulation parameters, different values of which lead to different system solutions. Hence, this last level enables the simulation capabilities for evaluation of alternatives. The resource information in Resources element, in Seize blocks and in Release blocks and the duration information in Delay block are in compliance with the initial values set in the SysML model. Model view for the second level activity AD1 is given in Figure 5.3 as an example.

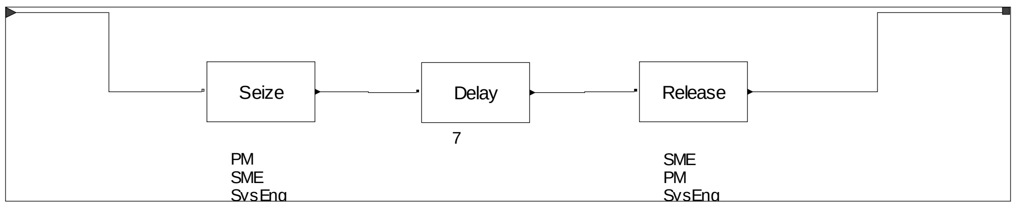


Figure 5.3 Arena Model View of Submodel AD1

5.2 MODEL TRANSFORMATION

In Section 5.1, Base Arena Model was defined. This model, together with the SysML model, establishes the starting point to the model transformation process. A map of the transformation process is given in Figure 5.4. Once the Modified Base Model in Excel is obtained, the first two boxes displayed in dashed lines are omitted for the alternatives analysis. The process is detailed in the following paragraphs.

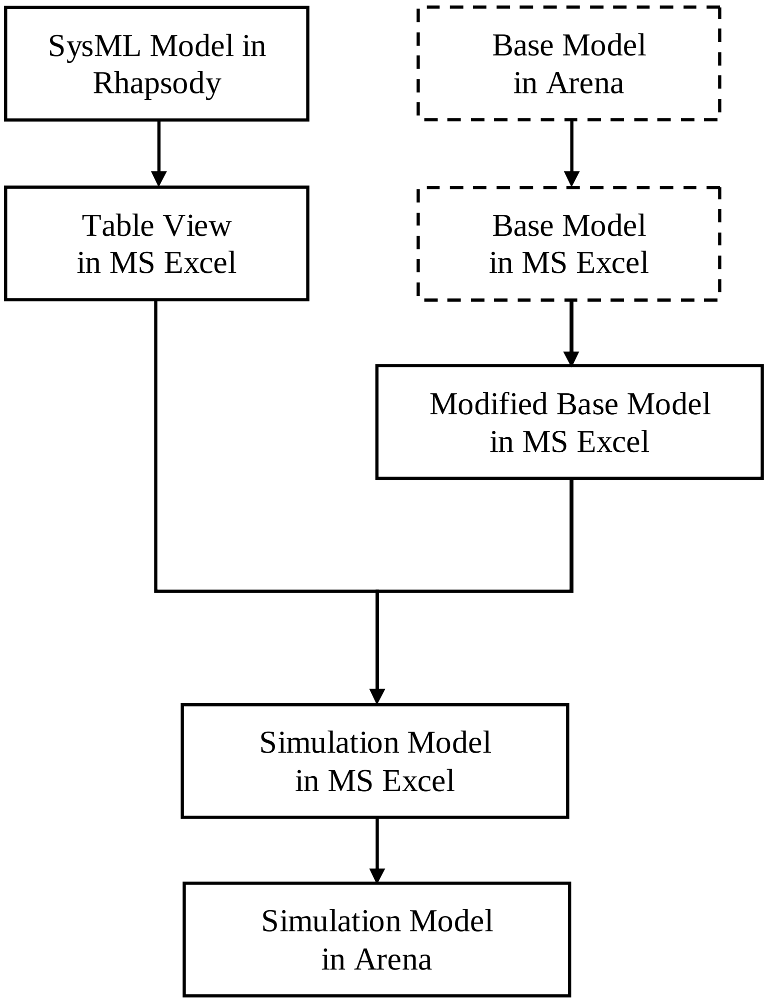


Figure 5.4 Model Transformation Process

Arena provides interface to both Access and Excel by the export functionality. In this study, the Excel interface is preferred. The base model is first developed in Arena and then exported to Excel for further modification. The Base Model in Excel includes the resource requirements and duration information for the second level systems engineering activities and resource availability within its tabs, namely Blocks Seize Resources, Blocks Release Resources, Blocks Delay and Elements Resources. The rest of the file includes necessary information to build the model in compliance with the conceptual model. This file is modified to remove the resource capacities, resource requirements and activity durations to obtain the Modified Base Model in Excel, which will be used to obtain the final simulation model with the actual input parameter values.

As described in Chapter 4, Table View of the SysML model includes the activities, resource requirements and duration values for the activities, and resource availabilities. This reflects the part of the model that provides the input parameters and is to be transferred to the simulation environment. Although a SysML model can be exported as an XMI file, it is not the only method to extract the necessary information. Since information to be transferred is already included in the Table View, the table is directly copied to an Excel file. Transformation of the Table View in Excel to the final Simulation Model in Excel, was achieved via running VBA codes and using the Modified Base Model in Excel.

The first VBA code named “Rearrange”, firstly copies available resource quantities to “Elements Resources Resources” tab of the Modified Base Model in Excel. Then the macro distributes duration and resource requirements to columns and deletes the rows for first level activities since they do not include any information to be transferred to the simulation. VBA code for the macro Rearrange is given in Appendix D.1.

The second and the third VBA codes provide transformation of the file into the format required by Arena. Using the second VBA code named “Macro_Transfer”, firstly the activities are listed in the order required by Arena import. Then, activity duration values are transferred to the “Blocks Delay” tab of the Modified Base Model in Excel. Afterwards, resource requirements are transferred to “Blocks Release Resources” tab. Similarly, using the third VBA code named

“Macro_Transfer2”, resource requirements are transferred to “Blocks Seize Resources” tab of the Modified Base Model in Excel. At the end, Simulation Model in Excel is obtained. VBA codes for Macro_Transfer and Macro_Transfer2 are given in Appendix D.2 and Appendix D.3, respectively. Finally, Simulation Model in Excel is imported to Arena and “Simulation Model in Arena”, which is ready to be run, is obtained.

In order to have different system alternatives in the simulation environment, Table View is updated to reflect the resource requirements and durations of activities in that alternative. The VBA codes are run on the Table View of concern and the resultant simulation model in Arena is obtained. Simulation cases for system alternatives and the run results are discussed in Chapter 6.

CHAPTER 6

VERIFICATION CASE STUDIES AND RESULTS

In this chapter, case studies and their results are introduced. In Section 6.1 the cases, which denote system alternatives, are described. In Section 6.2 simulation results are given.

It should be noted that the purpose of these cases is only verification as opposed to validation and true system performance evaluation. Hence, they are hypothetical cases. Specifically, input parameter values (activity durations, resource requirements of activities, and resource availabilities) are not estimated based on data collected from a real life system. They are selected as “reasonable” values based on past experiences. Therefore, simulation results do not reflect true performance estimators. They should be used only to verify the model behavior by comparing the system alternatives based on “reasonable” results.

6.1 CASE STUDIES

Conceptual model formation, model implementation in SysML and model transformation to Arena for simulation were described in Chapter 3, Chapter 4 and Chapter 5, respectively. These three chapters describe the modeling and simulation approach for the systems engineering process of aerospace design projects.

In developing the simulation model, initial input parameter values were used for several activities as stated in Section 4.2. Although the current Arena model can be run and simulation results for this unique case can be obtained, the simulation process is to be extended to verify the simulation model developed in our study. In order to observe the performance of the system with changing input parameters and to evaluate system alternatives , different cases are defined in this chapter. The proposed approach is conducted for these cases and simulation results are obtained. In this section, the cases are introduced.

Cases are determined based on the following three criteria: scale of the project as “small” or “large”, resource availability as “high” or “low” and activity duration type as “deterministic” or “stochastic”. Duration of each second level systems engineering activity and availabilities of each resource type are adjusted accordingly.

Properties of simulation cases are given in Table 6.1. The first three cases include deterministic activity durations. D1 can be regarded as the base case, where all parameters are set to the same values as the initial ones defined for model building process in Section 4.2. D1 denotes the small scale, low resource availability and deterministic activity durations. D2 is generated by multiplying the activity durations of D1 by a factor of 2.0 to obtain the large scale, low resource availability and deterministic activity durations case. D3 is generated by multiplying the activity durations and resource availability values of D1 by a factor of 2.0 to obtain the large scale, large resource availability and deterministic activity durations case. Individual activity resource requirements and durations for deterministic cases are given in Table E.1 in Appendix E.

Cases S1, S2 and S3 reflect stochastic activity duration versions of D1, D2 and D3, respectively. Meredith [21] suggests to use triangular distribution to analyze risk and manage the uncertainty in activity durations. Also, it is common practice in simulation to use triangular distribution when there are no data to determine the probability distributions [22]. Hence, triangular distribution is used in order to set stochastic activity durations. Minimum and mode values are remained as they are in the deterministic cases. Maximum values are obtained by multiplying the minimum/mode values by a factor of 1.5 or 2.0, depending on the risk associated with each activity. A high risk activity is considered as an activity that might lead to iterations within the activity itself and hence might have a more extended duration than expected. For low risk activities value in deterministic case is multiplied by 1.5. Second level activities of SRD, MA, RA, FA, SS and AD are treated as high risk activities and the rest as low risk activities. Individual activity resource requirements and durations for stochastic cases are given in Table E.2 in Appendix E.

Table 6.1 Properties of Simulation Cases

Case Number	Case Description	Resource Availability			Activity Durations
		SysEng	SME	PM	
D1	Small Scale and Low Resource Availability	10	30	2	Constant (c)
D2	Large Scale and Low Resource Availability	10	30	2	Constant (2c)
D3	Large Scale and High Resource Availability	20	60	4	Constant (2c)
S1	Small Scale and Low Resource Availability	10	30	2	Triangular (c, c, 2c) for high risk activities Triangular (c, c, 1.5c) for low risk activities
S2	Large Scale and Low Resource Availability	10	30	2	Triangular (2c, 2c, 4c) for high risk activities Triangular (2c, 2c, 3c) for low risk activities
S3	Large Scale and High Resource Availability	20	60	4	Triangular (2c, 2c, 4c) for high risk activities Triangular (2c, 2c, 3c) for low risk activities

6.2 CASE STUDY RESULTS

Given the cases to evaluate systems engineering process alternatives in Section 6.1, this section includes simulation results. Before implementing the cases in the proposed method, a step in model verification is conducted using the critical path method. Among the initial parameters set in Chapter 4 (also used in Case D1), activity durations are kept as they are while available resource quantities are increased to a large figure such as 500, which cannot be reached in all cases, in order to represent unlimited resources. This parameter set forms the base case.

Following the critical path method for the base case, critical activities are obtained as follows: SRD1, SRD2, SRD3, RA3, RA4, RA5, FA1, FA2, SS1, SS2, INT1, INT2, INT3, INT4, INT5, INT6, VER1, VER2, VER3, VER4, VAL1, VAL2, VAL3, VAL5, VAL6, VAL7, VAL8, MAINT1, MAINT2, MAINT3, MAINT5, MAINT7 / MAINT8 (Or OP1, OP2, OP3 / OP4 / OP5 instead of MAINT activities), DIS1, DIS2 / DIS 3, DIS 4, DIS5, DIS6. Project duration for the base case is obtained as 255, accordingly. Critical path for the first level systems engineering activities is given in bold in Figure 6.1. Critical path for a section of second level systems engineering activities is given in Figure 6.2.

In order to complete this step of verification, initial SysML model introduced in Chapter 4 is modified for unlimited resources, in compliance with the base case. When the proposed approach is conducted, 255 days are obtained as the project duration. Hence, the critical path method and the proposed approach resulted in the same value of project duration for the base case.

Completing this step, the first three cases with deterministic activity durations are regarded as inputs and the proposed method is run. Firstly, D1 is implemented in the SysML model, modifying the model to include activity durations, resource availabilities and resource requirements of D1. Model transformation to Arena and simulation run are conducted and results are obtained. Results include project duration in terms of work days and the resource utilizations in percentages. The same process is repeated for remaining deterministic cases D2 and D3. Results are included in Table 6.2.

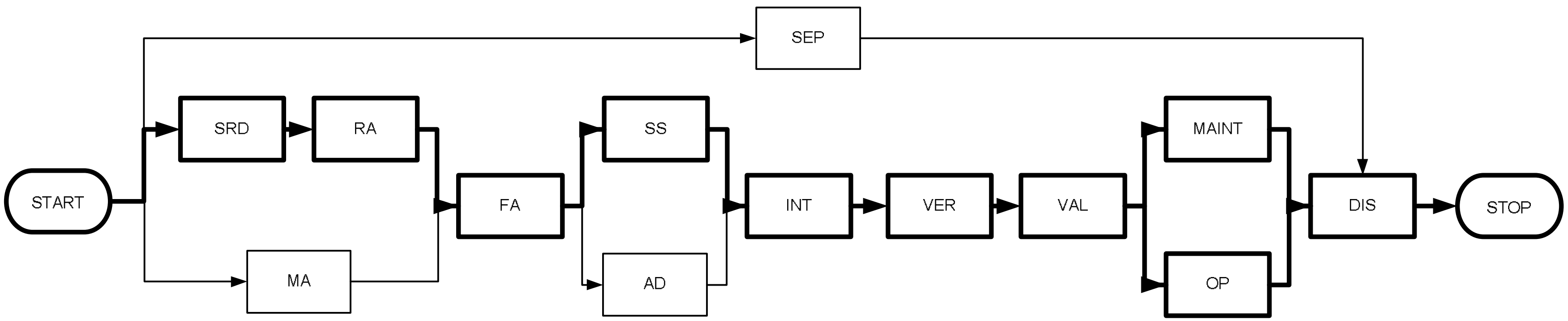


Figure 6.1 Critical Path for First Level Activity Network

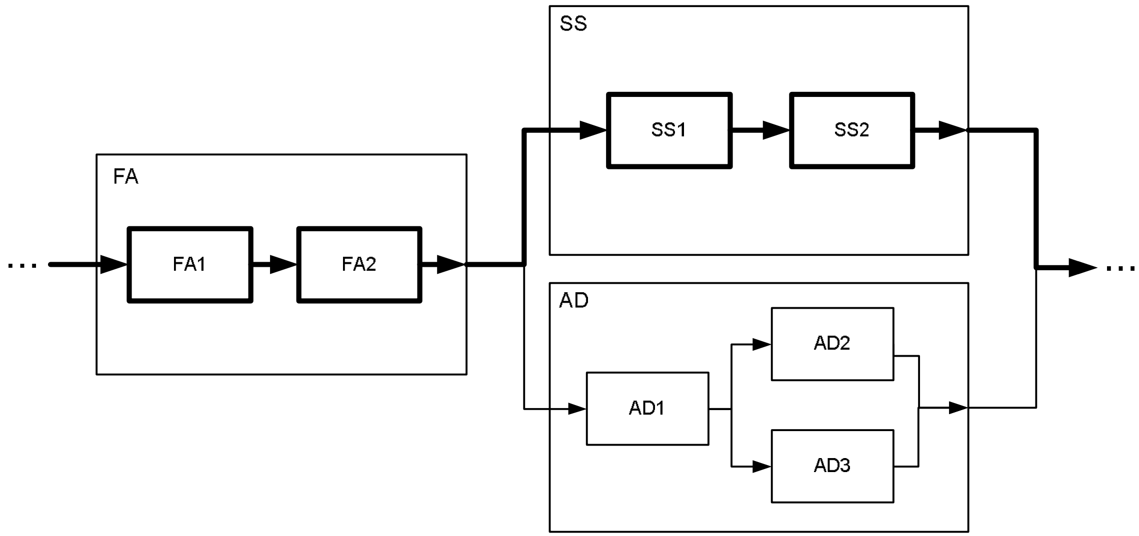


Figure 6.2 Critical Path for Partial Second Level Activity Network

Table 6.2 Average Results for Simulation Cases

	Base Case	Case D1	Case S1*	Case D2	Case S2*	Case D3	Case S3*
Critical Path With Unlimited Resources	255.0	255.0	310.8	510.0	621.7	510.0	621.7
Project Duration (Work Days)	255.0	378.0	455.3	756.0	910.7	626.0	758.3
SysEng Utilization (%)	-	34.1	34.8	34.1	34.8	20.6	21.0
SME Utilization (%)	-	51.5	51.7	51.5	51.7	31.1	31.0
PM Utilization (%)	-	29.8	29.4	29.8	29.4	18.0	17.9

* For stochastic cases, "critical path" is the sum of the expected durations of the activities that are on the critical path. Project duration and resource utilizations are averages of 10 replications.

For the cases with stochastic activity durations (S1, S2 and S3), determining the number of replications and constructing a confidence interval (CI) is a concern. As stated in Law and Kelton [22], considering a sample $Y_1, Y_2, \ldots, Y_m$ obtained from m replications and $\overline{Y} = \frac{1}{m}\sum_{i=1}^{m} Y_i$, if $Y_1, Y_2, \ldots, Y_m$ are independent and normally distributed, classical estimation theory can be used to construct a CI for $E(\overline{Y})$.

Stochastic activity durations lead to different simulation results in each replication, in terms of project duration and resource utilizations. Since system state is initialized at the beginning of each replication, different random variables are used and the values in each replication are independent from each other [22]. Although activity durations are subject to triangular distribution, normal distribution can be assumed according to Central Limit Theorem, since the observed duration in each replication means completion of all activities and the number of activities is not small.

Having project duration and resource utilizations independent and approximately normally distributed, a CI is determined in accordance with the algorithm proposed by Law and Kelton [22]. This algorithm defines the number of replications by managing the two conflicting objectives: high level of confidence (small α) and high precision (narrow CI width).

For each of the cases S1, S2 and S3 with stochastic activity durations, the following steps are conducted to establish/verify the number of replications needed to obtain the average values of project duration, SysEng utilization, SME utilization and PM utilization.

1. Initial number of replications is set.

   $n=n_0=10$

2. Average value across the replications is calculated.

   $$\overline{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$$

3. Variance of project duration among the replications is calculated.

   $$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(Y_i - \overline{Y})^2$$

4. α is selected as 0.10.
5. CI half length is calculated.

   $$h = t_{n-1,1-\alpha/2}\frac{s}{\sqrt{n}}$$

6. Relative precision (r) is selected as 0.10.
7. Desired half length is calculated.

   $$h^* = r\,\overline{Y}$$

8. If $h \le h^*$, iterations are sufficient, algorithm is terminated with CI $\overline{Y} \pm h$.

   Otherwise, the number of iterations is updated.

   $$n^* = \left\lfloor n\left(\frac{h}{h^*}\right)^2 \right\rfloor + 1$$

   n is set to n^*.

   Steps 1 to 8 are repeated.

The above algorithm is used for project duration in case S1 as an example below.

1. $n=n_0=10$
2. $\overline{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i = \frac{1}{10}$ (460.3 + 476.4 + 448.7 + 445.1 + 452.5 + 447.6 + 457.0 + 448.0 + 452.2 + 465.5)

   $\overline{Y} = 455.3$
3. Variance of project duration among the replications is calculated.

   $s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(Y_i - \overline{Y})^2 = \frac{1}{9}((460.3 - 455.3)^2 + (476.4 - 455.3)^2 + (448.7 - 455.3)^2 + (445.1 - 455.3)^2 + (452.5 - 455.3)^2 + (447.6 - 455.3)^2 + (457.0 - 455.3)^2 + (448.0 - 455.3)^2 + (452.2 - 455.3)^2 + (465.5 - 455.3)^2)$

   $s^2 = 94.8$
4. α is selected as 0.10.
5. CI half length is calculated using t-distribution [22].

   $h = t_{9,0.95}\frac{s}{\sqrt{n}} = 1.83\frac{9.7}{\sqrt{10}}$

   $h = 5.6$
6. Relative precision (r) is selected as 0.10.
7. Desired half length is calculated.

   $h^* = r\,\overline{Y} = (0.10)\,(455.3)$

   $h^* = 45.5$
8. Since $h \le h^*$, algorithm is terminated with CI 455.3 ± 5.6.

Therefore, 10 replications are sufficient for project duration estimation in S1. The same outcome is observed for the other simulation cases. For each of the cases S1, S2 and S3 with stochastic activity durations; 10 replications are found sufficient for a reasonable estimation of project duration, SysEng utilization, SME utilization and PM utilization. Step-by-step results for replication number estimation algorithm are given in Appendix F. Confidence intervals for stochastic simulation cases are summarized Table 6.3.

Table 6.3 Confidence Intervals for Stochastic Simulation Cases (α=0.10)

	Case S1		**Case S2**		**Case S3**	
	Standard Deviation	**Confidence Interval Limits**	**Standard Deviation**	**Confidence Interval Limits**	**Standard Deviation**	**Confidence Interval Limits**
Project Duration*	3.1	449.7, 461.0	6.2	899.4, 922.0	7.1	745.3, 771.3
SysEng Utilization (%)*	0.2	34.5, 35.2	0.2	34.5, 35.2	0.1	20.7, 21.2
SME Utilization (%)*	0.2	51.3, 52.1	0.2	51.3, 52.1	0.3	30.5, 31.6
PM Utilization (%)*	0.3	28.9, 29.9	0.3	28.9, 29.9	0.2	17.5, 18.4

* Project duration and utilization results are based on 10 replications

CHAPTER 7

CONCLUSIONS

The primary aim of this study is to model the systems engineering process of an aerospace design project and to generate a simulation model in order to evaluate the system performance. Although there exists a general understanding of the systems engineering concept, there is no unique definition for the process of systems engineering in terms of the activities included. The activities included, as well as the flow of these activities, depend highly upon the project of concern (i.e. modernization project, design project, production-only project etc.). This study considers systems engineering process of a real-life design project, addressing the whole life-cycle of the product. Product domain is identified as aerospace but no further limitations are specified.

A two-phase survey study is conducted in order to obtain a conceptual model for the systems engineering process. In each phase, ten systems engineers working in Helicopter Group in Turkish Aerospace Industries Inc. participated and stated their opinions related with the systems engineering process of a design project. The survey study is based on two references: Technical Processes defined in INCOSE Systems Engineering Handbook [1] and Systems Engineering Processes given in "Fundamentals of Modern Systems Engineering" short course of Georgia Tech [5]. At the end of the first phase, first level systems engineering activity network is obtained. This first level network provides an input to the second phase, where second level activity networks are defined. Hence, the conceptual model includes two levels of activity networks. One reason for this is the content of the references and another is to have a practical and reasonable model, which can further be developed to meet the needs of simulation. However, the model building methodology introduced in this study, has capabilities to reflect any level of abstraction due to object-oriented modeling characteristics.

Another aim is to implement the conceptual model in the object-oriented modeling environment, which provides a proper interface to systems engineers, project managers and even to the customer. SysML is used as the modeling language, since it is a standard language in systems engineering domain. Among the several diagram types that SysML features, block definition diagrams and activity diagrams are used in our study. By using block definition diagrams, the structural view of the system is defined, providing the hierarchical relations between system elements. On the other hand, activity diagrams reflect the behavior of the system by including the flow of activities.

In this study we also aim to transform the SysML model to a simulation environment and run the simulation to obtain results related with certain system characteristics such as project duration and resource utilizations. Therefore, an initial set of required parameters are embedded in the SysML model. These are resource availabilities, activity durations, and resource requirements of activities. The conceptual model is implemented in Arena to obtain a base model. The necessary parameters of the SysML model are then transferred to Excel and the final Excel file is obtained through VBA codes. By importing this final file to Arena, model to be simulated is achieved.

An ideal model is the one which can be verified and validated. By modifying the initial set of parameters in SysML model for unlimited resource availabilities and by applying the proposed method accordingly, project duration with unlimited resource availabilities is obtained. This result is compared by the manual critical path calculation and it is observed that the two results are compliant. Then, case studies are conducted to evaluate the system alternatives, which differ in scale of the project, in resource availabilities and also in the type of activity durations as deterministic or stochastic. Hence there are three cases for each of the deterministic and stochastic activity duration versions: small scale and low resource availability case, large scale and low resource availability case, large scale and high resource availability case.

The scale of the project is set as large or small by adjusting the activity durations. Similarly resource availabilities are changed among cases to evaluate its effect on the overall process. For stochastic activity durations, the deterministic values are taken as the minimum and mode of the triangular distribution and the maximum value is set as a factor of minimum/mode, where the factor depends on the risk expected for an activity.

As a result of the case studies, it is observed that project duration for stochastic activity duration cases are always higher than those of deterministic activity duration cases, as expected. When unlimited resources are assumed, small scale cases have shorter project durations than high scale cases. Assigning limited resource availabilities, the project duration increases in the order of small scale and low resource availability cases, large scale and large resource availability cases, large scale and low resource availability cases.

SME has the highest utilization values in all cases, followed by SysEng. PM has the lowest utilization. This is also expected since SMEs have different expertise areas and participate in several different steps of the whole process, while PMs take part in technical processes only when required.

Increasing the scale of the project does not affect the utilization value of any of the resources but leads to higher project completion times. This is expected since available resource quantities stay the same. Comparing two large scale cases, it is observed that with increasing resource availability, project completion time decreases both in deterministic and stochastic cases, while the utilization values drop. Hence, allocating resources to more than one project might be suitable for systems engineering process.

Prior to model building, the problem domain was set as a design project of aerospace products. Considering the design of less complex vehicles, might reduce the complexity of the conceptual model and might lead to a simpler model implementation, transformation and simulation process. On the other hand, design of a more complex system might require a higher abstraction level.

The conceptual model is based on two references. Although they’re well-known and authoritative in the field of systems engineering, the number of references can be extended in further studies or a new activity set can be formed by a larger group of people having knowledge and experience on the subject. The survey study respondents in this study are systems engineers, who have been working on real-life projects. However, they are experienced mainly in the aerospace domain. Therefore, shifting the domain would require to extend or to change the respondent profile. Two levels of networks are included within the conceptual model. Although this fits the projects of concern in our study, it should be noted that, with introduction of the second level networks, setting predecessor relations becomes more challenging for the survey respondents. Also the process of evaluating survey results becomes more complicated, which might lead to a decrease in the similarity of the conceptual model to a real life project.

While forming the second level activity networks in Phase 2 of the survey, second level activities of only the selected first level activities are used. Hence, only one of the two references is considered for each second level activity network. Another approach would be to combine the second level activities of the two references and ask the respondents to select the required ones from this mixed set. This is a more flexible solution but also more complicated since each of the references has their own detailed definitions of the second level activity groups. Moreover, in this case an additional step of selecting the second level activities before forming the networks would be added to Phase 2 of the survey.

Phase 2 of the survey is in compliance with the results of Phase 1. However, no iterations are followed. Although one of the group decision making techniques (i.e. Delphi technique, brainstorming etc.) were intended to be used, since the respondents had limited amount of time and since the available hours differed from person to person, surveys were conducted individually and once for each phase. Having no feedback from the final conceptual model to the respondents, the conceptual model could not be validated. A future study might consider a group decision making technique, which leads to conceptual model validation.

Model implementation in SysML, includes using activity diagrams and block definition diagrams. However, SysML offers a wide range of diagrams, each representing the system from a different perspective. Future studies might include modeling the inputs and outputs among system blocks, as well as modeling the requirements and their relations with the system.

Transformation of the SysML model to the simulation environment requires a base model to be created in Arena. The process of model transformation can be improved to omit the need for base model creation, being able to automatically create the necessary features in Excel. Using VBA codes to transform the SysML output to the necessary file for importing the model to Arena is an alternative approach to using XMI export functionality of SysML. However, the first step requires a manual copy-paste step, to transfer the SysML table view to the Excel file. In a future study, this process can be made fully-automatic by combining the use of XMI and VBA codes.

The cases formed for alternatives are hypothetical examples and are not based on data obtained from real life projects. Hence, the cases do not generate true estimates. They only provide examples to illustrate possible applications and verification of the proposed approach. Therefore, future work might include a specific case study, reflecting collection and statistical analysis of real life data.

In the case studies, the scale of the project is assumed to be dependent on the activity durations but not on the resource requirements of activities. Hence, activity durations are increased to simulate large scale. However, larger project scales can also be simulated considering higher resource requirements for activities. Moreover, a factor of two is used to multiply the small scale durations to obtain large scale durations for all activities. More realistic data can lead to different factors for different activities, since certain activity durations might only be slightly affected by the scale of the project (i.e. mission analysis) while others depend highly on the scale (i.e. integration). Regarding resource availabilities, again a factor of two is used to multiply the low resource availability cases to obtain high resource availability cases. Similarly, this factor can be re-adjusted according to more realistic data since high resource availability might mean higher quantities for certain resource types (i.e. SME) than the others (i.e. PM).

In order to observe the effect of uncertainty on the project performance, stochastic durations are assigned to activities. Triangular distribution is assumed since statistical data are not available and since stochastic durations is preferred to be easily related to the respective deterministic values. However, valid statistical data might fit better to another distribution. The effect of high risk is reflected on the project duration while maximum values of the triangular distribution is assigned. Activities up to integration are assumed to be high risk, due to the iterative nature of these activities at the initial stages of the project life cycle. However, the effect of risk originating from a high risk activity might also be observed at another stage (i.e. at later stages) of the project life cycle and hence might affect the duration of other activities as well. Defining high risk activities according to real-life statistical data and analyzing the effects of risk are considered as other future perspectives.

The proposed approach is considered as applicable to project management problems, providing certain advantages over the well-known project management tools and methods. Firstly, a realistic process network is achieved for design projects, where respondents are from the domain of concern and where their experiences are taken into consideration. Secondly, the approach allows conducting sensitivity analysis by assigning different resource availabilities and different resource requirements and durations for the activities. Hence the proposed approach does not address a pure scheduling solution but also provides means for “what if” analysis facilitating workload and activity duration estimation. Finally, the object-oriented methodology provides future extension capabilities to include the physical model of the product and link it to the processes obtained in this study.

In general, different phases of this thesis study such as systems engineering process definition, object-oriented model implementation, model transformation for simulation and sensitivity analysis are applicable for today’s complex system design and project management issues and are subject to further studies and improvements.

REFERENCES

[1] International Council on Systems Engineering (INCOSE), "Systems Engineering Handbook", Version 3.2, 2010

[2] Joint OSD/Services/Industry Working Group, "MIL-STD-499B (DRAFT), Draft Military Standard: Systems Engineering", 1993

[3] Weilkiens, T., "Systems Engineering with SysML/UML", Morgan Kaufmann OMG Press, 2008

[4] Arnold, S., Lawson, H.W., "Viewing Systems from a Business Management Perspective: The ISO/IEC 15288 Standard", Systems Engineering, vol. 7, iss. 3, pp. 229–242, Wiley Subscription Services, Inc., 2004

[5] Georgia Institute of Technology, Short Course: "Fundamentals of Modern Systems Engineering", Georgia Tech Distance Learning and Professional Education, 2011

[6] Booch, G., "Object-oriented Analysis and Design", 2nd ed., Addison-Wesley Longman, 1994

[7] Object Management Group (OMG), "OMG Unified Modeling Language™ (OMG UML), Infrastructure Specification", Version 2.4.1, 2011

[8] Object Management Group (OMG), "OMG Unified Modeling Language™ (OMG UML), Superstructure Specification", Version 2.4.1, 2011

[9] Object Management Group (OMG), "OMG Systems Modeling Language (OMG SysML™) Specification", Version 1.3, 2012

[10] Anglani, A., Grieco, A., Pacella, M., Tolio, T., “Object-oriented Modeling and Simulation of Flexible Manufacturing Systems: a Rule-based Procedure”, Simulation Modelling Practice and Theory, vol. 10, no. 3-4, pp. 209-234, 2002

[11] Constant, O., Monin, W., Graf, S., “A Model Transformation Tool for Performance Simulation of Complex UML Models”, Companion of the 30th International conference on Software engineering, pp. 923-924, 2008

[12] Huang, E., Ramamurthy, R., McGinnis, L.F., “System and Simulation Modeling Using SysML”, Proceedings of the 2007 Winter Simulation Conference, 2007

[13] Liehr, A.W., Buchenrieder, K.J., “An XML Based Simulation Method for Extended Queuing Networks”, Proceedings of the 22nd European Conference on Modelling and Simulation, pp. 322–328, 2008

[14] Liehr, A.W., Buchenrieder, K.J., “Transforming UML-Based System Descriptions into Simulation Models as Part of System Development Frameworks”, 12th International Conference on Computer Aided Systems Theory Lecture Notes in Computer Science, vol. 5717, pp.857-864, 2009

[15] Johnson, T., Paredis, C.J.J., Burkhart, R., “Integrating Models and Simulations of Continuous Dynamics into SysML”, Proceedings of Modelica Conference, 2008

[16] Nikolaidou, M., Dalakas, Mitsi, L., Kapos, G., Anagnostopoulos, D., “A SysML Profile for Classical DEVS Simulators”, Proceedings of International Conference on Software Engineering Advances, pp. 445–450, 2008

[17] Wang, R., Dagli, C.H., “An Executable System Architecture Approach to Discrete Events System Modeling Using SysML in Conjunction with Colored Petri Net”, Proceedings of IEEE Systems Conference, pp. 1–8, 2008

[18] Nikolaidou, M., Dalakas, V., Anagnostopoulos, D., "Integrating Simulation Capabilities in SysML using DEVS", Proceedings of IEEE Systems Conference, 2010

[19] Schönherr, O., Rose, O., "First Steps Towards A General Sysml Model For Discrete Processes In Production Systems", Proceedings of the 2009 Winter Simulation Conference, 2009

[20] McGinnis, L., Ustun, V., "A Simple Example Of Sysml-Driven Simulation", Proceedings of the 2009 Winter Simulation Conference, 2009

[21] Meredith, J.R., Mantel, S.J., "Project Management: A Managerial Approach", 6th ed., John Wiley & Sons, 2006

[22] Law, A.M., Kelton, W.D., "Simulation Modeling & Analysis", 2^{nd} ed., McGraw-Hill, 1991

APPENDIX A

QUESTIONNAIRE SURVEY STUDIES

A.1 QUESTIONNAIRE SURVEY STUDY – PHASE 1

QUESTIONNAIRE 1 – Systems Engineering Process First Level Activities

Name:

Surname:

Number of years of work experience in systems engineering:

PART 1

In the following table, a list of potential activities and their purposes/definitions are given according to two widely accepted systems engineering references. Please read the purpose/definition of each activity and check the "Included or Not" column, if you think the corresponding activity should be included and identified separately in the systems engineering process of a real-world design project conducted in your organization.

If you think that two or more activities overlap, please choose the one you prefer the most according to the process definitions.

If you think that the activity is a subactivity of another main activity, please leave the box unchecked. This questionnaire should include only the first level (high level) activities

.

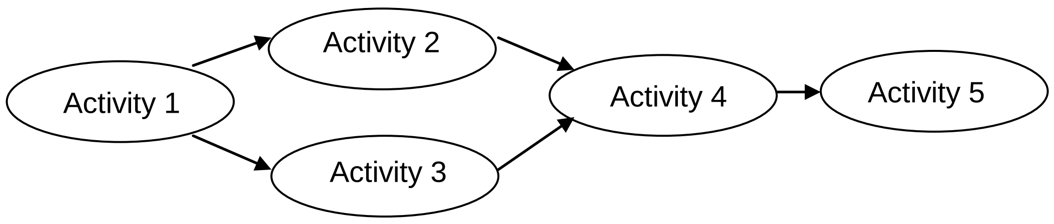
Activity Code	Reference 1 Activity Name and Purpose	Reference 2 Activity Name and Purpose	Included or Not
SRD	Stakeholder Requirements Definition *Define the requirements for a system that can provide the services needed by users and other stakeholders in a defined environment*		
MA		Mission Analysis *Determine problem / opportunity, identify potential customers and stakeholder, collect high-level desirements*	
RA	Requirements Analysis *Transform the stakeholder, requirement-driven view of desired services into a technical view of a required product that could deliver those services*	Requirements Analysis *Define system customers, determine requirements from desirements, validate system requirementswith system customers*	
BM		Baseline Management: *Establish initial system baselines, control changes to baselines as system definition matures*	
FA		Functional Analysis *Identify system functionality in generic terms, validate completeness of functional system description*	
TS		Tradeoff Studies *Study various means of providing system functionality, remove unacceptable candidates from further consideration, identify any risks associated with acceptable functional candidates*	
AA		Alternative Analysis *Combine acceptable functions into alternative total system solutions, assess performance of system alternatives, select one or more preferred solutions*	
SS		System Synthesis *Identify physical components of preferred system solution(s), develop physical system architectures*	

Activity Code	**Reference 1 Activity Name and Purpose**	**Reference 2 Activity Name and Purpose**	**Included or Not**
AD	Architectural Design *Synthesize a solution that satisfies system requirements*		
IMP	Implementation *Realize a specified system element*		
INT	Integration *Assemble a system that is consistent with the architectural design*	Systems Integration *Define interfaces between physical system components, define interfaces between system and environment, determine controls and characteristics of all interfaces*	
VER	Verification *Confirm that the specified design requirements are fulfilled by the system*	System Verification *Test, inspect, simulate, etc. the physical architecture of preferred system solutions, identify and resolve any non-compliance with requirements*	
TRANS	Transition Establish a capability to provide services specified by stakeholder requirements in the operational environment		
VAL	Validation Provide objective evidence that the services provided by a system when in use comply with stakeholders' requirements, achieving its intended use in its intended environment		
OP	Operation Use the system in order to deliver its services		
MAINT	Maintenance Sustain the capability of the system to provide a service		
DIS	Disposal End the existence of a system entity		
SEP		Systems Engineering Planning Plan for the total systems engineering effort on a project, integrate with project management activities	

PART 2

Please construct a precedence network including the activities you selected in Part 1 and using the activity codes in the table.

Your network should look like this:



Precedence Network

A.2 QUESTIONNAIRE SURVEY STUDY – PHASE 2

QUESTIONNAIRE 2 – Systems Engineering Process Second Level Activities

Name:

Surname:

Number of years of work experience in systems engineering:

PART 1

In the following table, three activities and corresponding subactivities are given according to two widely accepted systems engineering references. Please read the activities & subactivities and in the last column note the name of reference (as "Reference 1" or "Reference 2") which you think includes the most appropriate subactivities for the related activity.

Activity	Reference 1 Subactivities	Reference 2 Subactivities	Selected Reference
RA Requirements Analysis	1. Define the System Requirements 2. Analyze and Maintain the System Requirements	1. Define System Customers 2. Determine Requirements from "desirements" 3. Validate system requirements with system customers	
INT Integration	Plan Integration 1. Define integration strategy 2. Schedule integration testing tools and facilities Perform Integration 3. Assemble system elements according to the integration plan 4. Validate and Verify Interfaces 5. Verify and Analyze Assemblies 6. Document integration testing and analysis results 7. Document and control the architectural baseline	1. Define interfaces between physical system components 2. Define interfaces between system and environment 3. Determine control and characteristics of all interfaces	

Activity	Reference 1 Subactivities	Reference 2 Subactivities	Selected Reference
VER Verification	Plan Verification 1. Schedule, confirm and install verification enabling systems Perform Verification 2. Develop verification procedures 3. Conduct verification activities per established procedures, to demonstrate compliance with requirements 4. Document verification results and enter data into the Requirements Verification and Traceability Matrix	1. Test, inspect, simulate, etc. the physical architecture of preferred system solutions 2. Identify and resolve any non-compliance with requirements	

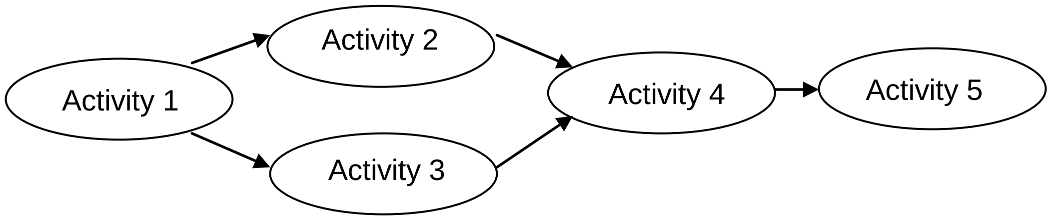
PART 2

An activity and corresponding subactivities are given in each of the tables below. For each activity, please read the subactivities and construct a precedence network including the subactivities. While constructing the network please use the subactivity codes, which are given in parenthesis following each subactivity name.

For Requirements Analysis (RA), Integration (INT) and Verification (VER) activities, please use all of the subactivities corresponding to your reference selection in Part 1.

For rest of the activities, please use all of the subactivities given in related table.

A network should look like this:



1. Stakeholder Requirements Definition:

Activity	Subactivities and Subactivity Codes
SRD Stakeholder Requirements Definition	1. Elicit stakeholder requirements (SRD1) 2. Define stakeholder requirements (SRD2) 3. Analyze and maintain stakeholder requirements (SRD3)

Precedence Network for Stakeholder Requirements Definition:

2. Mission Analysis:

Activity	Subactivities and Subactivity Codes
MA Mission Analysis	1. Determine problem/opportunity (MA1) 2. Identify potential customers and stakeholder (MA2) 3. Collect high-level desirements (MA3)

Precedence Network for Mission Analysis:

3. Requirements Analysis:

Activity	Reference 1 Subactivities and Subactivity Codes	Reference 2 Subactivities and Subactivity Codes
RA Requirements Analysis	1. Define the system requirements (RA1) 2. Analyze and maintain the system requirements (RA2)	1. Define System Customers (RA3) 2. Determine Requirements from "desirements" (RA4) 3. Validate system requirements with system customers (RA5)

Precedence Network for Requirements Analysis:

4. Functional Analysis:

Activity	Subactivities and Subactivity Codes
FA Functional Analysis	1. Identify system functionality in generic terms (FA1) 2. Validate completeness of functional system description (FA2)

Precedence Network for Functional Analysis:

5. System Synthesis:

Activity	Subactivities and Subactivity Codes
SS System Synthesis	1. Identify physical components of preferred system solution(s) (SS1) 2. Develop physical system architectures (SS2)

Precedence Network for System Synthesis:

6. Architectural Design:

Activity	Subactivities and Subactivity Codes
AD Architectural Design	1. Define the architecture (AD1) 2. Analyze and evaluate the architecture (AD2) 3. Document and maintain the architecture (AD3)

Precedence Network for Architectural Design:

7. Integration:

Activity	Reference 1 Subactivities and Subactivity Codes	Reference 2 Subactivities and Subactivity Codes
INT Integration	Plan Integration 1. Define the integration strategy (INT1) 2. Schedule integration testing tools and facilities (INT2) Perform Integration 3. Assemble system elements according to the integration plan (INT3) 4. Validate and verify interfaces (INT4) 5. Verify and analyze assemblies (INT5) 6. Document integration testing and analysis results (INT6) 7. Document and control the architectural baseline (INT7)	1. Define interfaces between physical system components (INT8) 2. Define interfaces between system and environment (INT9) 3. Determine control and characteristics of all interfaces (INT10)

Precedence Network for Integration:

8. Verification:

Activity	Reference 1 Subactivities and Subactivity Codes	Reference 2 Subactivities and Subactivity Codes
VER Verification	Plan Verification 1. Schedule, confirm and install verification enabling systems (VER1) Perform Verification 2. Develop verification procedures (VER2) 3. Conduct verification activities, per established procedures, to demonstrate compliance with requirements (VER3) 4. Document verification results and enter data into the Requirements Verification and Traceability Matrix (VER4)	1. Test, inspect, simulate, etc. the physical architecture of preferred system solutions (VER5) 2. Identify and resolve any non-compliance with requirements (VER6)

Precedence Network for Verification:

9. Validation:

Activity	Subactivities and Subactivity Codes
VAL Validation	Plan Validation 1. Develop a validation strategy (VAL1) Perform Validation 2. Develop validation procedures that demonstrate that the system is fit for its purpose and satisfies the stakeholders' requirements (VAL2) 3. Ensure readiness to conduct validation (VAL3) 4. Support in-process validation throughout system development (VAL4) 5. Conduct validation to demonstrate conformance to stakeholder requirements (VAL5) 6. If anomalies are detected, analyze for corrective actions and detect trends in failure to find threats to the system and evidence of design errors (VAL6) 7. Recommend corrective actions and obtain stakeholder acceptance of validation results (VAL7) 8. Document validation results and enter data into the Requirements Verification and Traceability Matrix (VAL8)

Precedence Network for Validation:

10. Maintenance:

Activity	Subactivities and Subactivity Codes
MAINT Maintenance	Plan Maintenance 1. Establish a maintenance strategy (MAINT1) 2. Define maintenance constraints on the system requirements (MAINT2) 3. Obtain the enabling systems, system elements and other services used for maintenance of the system (MAINT3) 4. Monitor replenishment levels of spare parts (MAINT4) 5. Manage the skills and availability of trained maintenance personnel (MAINT5) Perform Maintenance 6. Implement maintenance and problem resolving procedures (MAINT6) 7. Maintain a history of failures, actions taken and other trends to inform operations and maintenance personnel and other projects creating or utilizing similar system elements (MAINT7) 8. Monitor customer satisfaction with system and maintenance support (MAINT8)

Precedence Network for Maintenance:

11. Operation:

Activity	Subactivities and Subactivity Codes
OP Operation	1. Prepare for operation (OP1) 2. Perform operational activation and check-out (OP2) 3. Use system for operations (OP3) 4. Perform operational problem resolution (OP4) 5. Support the customer (OP5)

Precedence Network for Operation:

12. Disposal:

Activity	Subactivities and Subactivity Codes
DIS Disposal	Plan Disposal 1. Review the concept of disposal (DIS1) 2. Define the disposal strategy (DIS2) 3. Impose associated constraints on the system requirements (DIS3) Perform Disposal 4. Deactivate the elements to be terminated (DIS4) 5. Disassemble the elements for ease of handling (DIS5) 6. Remove the elements and any associated waste products from the operational site (DIS6) Finalize the Disposal 7. Maintain the documentation of all disposal activities and residual hazards (DIS7)

Precedence Network for Disposal:

13. Systems Engineering Planning:

Activity	Subactivities and Subactivity Codes
SEP Systems Engineering Planning	1. Plan for the total systems engineering effort on a project (SEP1) 2. Integrate with project management activities (SEP2)

Precedence Network for Systems Engineering Planning:

APPENDIX B

SURVEY STUDY RESULTS

Table B.1 Predecessor Selection in Phase 1

		Respondent Reference (j):									
Activity (i)	**Candidate Predecessors for Activity i (k):**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
SRD	**MA**	0	0	0	0	0	0	0	**1**	0	0
	RA	0	0	0	0	0	0	0	0	0	0
	FA	0	0	0	0	0	0	0	0	0	0
	SS	0	0	0	0	0	0	0	0	0	0
	AD	0	0	0	0	0	0	0	0	0	0
	INT	0	0	0	0	0	0	0	0	0	0
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	0	0	0	0	0	0	0	**1**	0	0
MA	**SRD**	0	0	**1**	0	0	**1**	0	0	0	0
	RA	0	0	0	0	0	0	0	0	0	0
	FA	0	0	0	0	0	0	0	0	0	0
	SS	0	0	0	0	0	0	0	0	0	0
	AD	0	0	0	0	0	0	0	0	0	0
	INT	0	0	0	0	0	0	0	0	0	0
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	**1**	0	0	0	0	0	0	**1**	**1**	0

Table B.1 Predecessor Selection in Phase 1 (Continued)

		Respondent Reference (j):									
Activity (i)	**Candidate Predecessors for Activity i (k):**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RA	**SRD**	0	0	**1**	0	0	**1**	**1**	0	0	**1**
	MA	**1**	**1**	0	0	**1**	0	0	**1**	**1**	0
	FA	0	0	0	0	0	0	0	0	0	0
	SS	0	0	0	0	0	0	0	0	0	0
	AD	0	0	0	0	0	0	0	0	0	0
	INT	0	0	0	0	0	0	0	0	0	0
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	**1**	0	0	0	0	0	0	**1**	**1**	0
FA	**SRD**	0	0	**1**	0	0	**1**	**1**	**1**	0	0
	MA	**1**	**1**	**1**	0	**1**	**1**	0	**1**	**1**	0
	RA	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0
	SS	0	0	0	0	0	0	0	0	0	0
	AD	0	0	0	0	0	0	0	0	0	0
	INT	0	0	0	0	0	0	0	0	0	0
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	**1**	0	0	0	0	0	0	**1**	**1**	0
SS	**SRD**	0	0	**1**	0	0	**1**	0	**1**	0	0
	MA	0	**1**	**1**	0	**1**	**1**	0	**1**	**1**	0
	RA	0	**1**	**1**	0	**1**	**1**	0	**1**	**1**	0
	FA	0	**1**	**1**	0	**1**	**1**	0	**1**	**1**	0
	AD	0	0	0	0	0	0	0	0	0	0
	INT	0	0	0	0	0	0	0	0	0	0
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	0	0	0	0	0	0	0	**1**	**1**	0
AD	**SRD**	0	0	0	0	0	0	**1**	**1**	0	**1**
	MA	**1**	**1**	0	0	0	0	0	**1**	**1**	0
	RA	**1**	**1**	0	**1**	0	0	**1**	**1**	**1**	**1**
	FA	**1**	**1**	0	**1**	0	0	**1**	**1**	0	0
	SS	0	**1**	0	0	0	0	0	0	0	0
	INT	0	0	0	0	0	0	0	0	0	0
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	**1**	0	0	0	0	0	0	**1**	**1**	0
INT	**SRD**	0	0	**1**	0	0	**1**	**1**	**1**	0	**1**
	MA	**1**	**1**	**1**	0	**1**	**1**	0	**1**	**1**	0
	RA	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**

Table B.1 Predecessor Selection in Phase 1 (Continued)

Activity (i)	Candidate Predecessors for Activity i (k):	Respondent Reference (j): 1	2	3	4	5	6	7	8	9	10
	FA	1	1	1	1	1	1	1	1	1	0
	SS	0	1	1	0	1	1	0	1	1	0
	AD	1	1	0	1	0	0	1	1	1	1
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	1	0	0	0	0	0	0	1	1	0
VER	SRD	0	0	1	0	0	1	1	1	0	1
	MA	1	1	1	0	1	1	0	1	1	0
	RA	1	1	1	1	1	1	1	1	1	1
	FA	1	1	1	1	1	1	1	1	1	0
	SS	0	1	1	0	1	1	0	1	1	0
	AD	1	1	0	1	0	0	1	1	1	1
	INT	1	1	1	1	1	1	1	1	1	1
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	1	0	0	1	0	0	0	1	1	0
VAL	SRD	0	0	1	0	0	1	1	0	0	1
	MA	1	1	1	0	1	1	0	0	1	0
	RA	1	1	1	1	1	1	1	0	1	1
	FA	1	1	1	1	1	1	1	0	1	0
	SS	0	1	1	0	1	1	0	0	1	0
	AD	1	1	0	1	0	0	1	0	1	1
	INT	1	1	1	1	1	1	1	0	1	1
	VER	0	1	1	0	0	1	0	0	1	1
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	1	0	0	1	0	0	1	0	1	0
OP	SRD	0	0	1	0	0	1	1	0	0	1
	MA	0	1	1	0	0	1	0	0	0	0
	RA	0	1	1	0	0	1	1	0	0	1
	FA	0	1	1	0	0	1	1	0	0	0
	SS	0	1	1	0	0	1	0	0	0	0
	AD	0	1	0	0	0	0	1	0	0	1
	INT	0	1	1	0	0	1	1	0	0	1
	VER	0	1	1	0	0	1	0	0	0	1
	VAL	0	1	1	0	0	1	1	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	0	0	0	0	0	0	1	0	0	0
MAINT	SRD	0	0	1	0	0	1	1	0	0	1
	MA	1	0	1	0	0	1	0	0	0	0
	RA	1	0	1	1	0	1	1	0	0	1
	FA	1	0	1	1	0	1	1	0	0	0
	SS	0	0	1	0	0	1	0	0	0	0
	AD	1	0	0	1	0	0	1	0	0	1

Table B.1 Predecessor Selection in Phase 1 (Continued)

		Respondent Reference (j):									
Activity (i)	**Candidate Predecessors for Activity i (k):**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	INT	1	0	1	1	0	1	1	0	0	1
	VER	1	0	1	1	0	1	0	0	0	1
	VAL	1	0	1	1	0	1	1	0	0	0
	OP	0	0	1	0	0	1	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0
	SEP	1	0	0	1	0	0	1	0	0	0
DIS	**SRD**	0	0	1	0	0	1	1	0	0	1
	MA	1	0	1	0	0	1	0	0	0	0
	RA	1	0	1	1	0	1	1	0	0	1
	FA	1	0	1	1	0	1	1	0	0	0
	SS	0	0	1	0	0	1	0	0	0	0
	AD	1	0	0	1	0	0	1	0	0	1
	INT	1	0	1	1	0	1	1	0	0	1
	VER	1	0	1	1	0	1	0	0	0	1
	VAL	1	0	1	1	0	1	1	0	0	1
	OP	0	0	1	0	0	1	1	0	0	1
	MAINT	1	0	1	1	0	1	1	0	0	1
	SEP	1	0	0	1	0	1	1	0	0	0
SEP	**SRD**	0	0	0	0	0	0	1	0	0	0
	MA	0	0	0	0	0	0	0	0	0	0
	RA	0	0	0	0	0	0	0	0	0	0
	FA	0	0	0	0	0	0	0	0	0	0
	SS	0	0	0	0	0	0	0	0	0	0
	AD	0	0	0	0	0	0	0	0	0	0
	INT	0	0	0	0	0	0	0	0	0	0
	VER	0	0	0	0	0	0	0	0	0	0
	VAL	0	0	0	0	0	0	0	0	0	0
	OP	0	0	0	0	0	0	0	0	0	0
	MAINT	0	0	0	0	0	0	0	0	0	0
	DIS	0	0	0	0	0	0	0	0	0	0

Table B.2 Predecessor Scores in Phase 1

Activity (i)	Candidate Predecessors for Activity i (k):	Weighted Predecessor Score (WPSik)	WASi	WPSik / WASi
SRD	**MA**	0.15	0.68	0.22
	RA	0.00	0.68	0.00
	FA	0.00	0.68	0.00
	SS	0.00	0.68	0.00
	AD	0.00	0.68	0.00
	INT	0.00	0.68	0.00
	VER	0.00	0.68	0.00
	VAL	0.00	0.68	0.00
	OP	0.00	0.68	0.00
	MAINT	0.00	0.68	0.00
	DIS	0.00	0.68	0.00
	SEP	0.15	0.68	0.22
MA	**SRD**	0.18	0.53	0.33
	RA	0.00	0.53	0.00
	FA	0.00	0.53	0.00
	SS	0.00	0.53	0.00
	AD	0.00	0.53	0.00
	INT	0.00	0.53	0.00
	VER	0.00	0.53	0.00
	VAL	0.00	0.53	0.00
	OP	0.00	0.53	0.00
	MAINT	0.00	0.53	0.00
	DIS	0.00	0.53	0.00
	SEP	0.26	0.53	0.50
RA	**SRD**	0.53	1.00	0.53
	MA	0.35	1.00	0.35
	FA	0.00	1.00	0.00
	SS	0.00	1.00	0.00
	AD	0.00	1.00	0.00
	INT	0.00	1.00	0.00
	VER	0.00	1.00	0.00
	VAL	0.00	1.00	0.00
	OP	0.00	1.00	0.00
	MAINT	0.00	1.00	0.00
	DIS	0.00	1.00	0.00
	SEP	0.26	1.00	0.26

Table B.2 Predecessor Scores in Phase 1 (Continued)

Activity (i)	Candidate Predecessors for Activity i (k):	Weighted Predecessor Score (WPSik)	WASi	WPSik / WASi
FA	**SRD**	0.41	0.74	0.56
	MA	0.53	0.74	0.72
	RA	0.74	0.74	1.00
	SS	0.00	0.74	0.00
	AD	0.00	0.74	0.00
	INT	0.00	0.74	0.00
	VER	0.00	0.74	0.00
	VAL	0.00	0.74	0.00
	OP	0.00	0.74	0.00
	MAINT	0.00	0.74	0.00
	DIS	0.00	0.74	0.00
	SEP	0.26	0.74	0.36
SS	**SRD**	0.32	0.50	0.65
	MA	0.50	0.50	1.00
	RA	0.50	0.50	1.00
	FA	0.50	0.50	1.00
	AD	0.00	0.50	0.00
	INT	0.00	0.50	0.00
	VER	0.00	0.50	0.00
	VAL	0.00	0.50	0.00
	OP	0.00	0.50	0.00
	MAINT	0.00	0.50	0.00
	DIS	0.00	0.50	0.00
	SEP	0.24	0.50	0.47
AD	**SRD**	0.50	0.79	0.63
	MA	0.32	0.79	0.41
	RA	0.79	0.79	1.00
	FA	0.44	0.79	0.56
	SS	0.06	0.79	0.07
	INT	0.00	0.79	0.00
	VER	0.00	0.79	0.00
	VAL	0.00	0.79	0.00
	OP	0.00	0.79	0.00
	MAINT	0.00	0.79	0.00
	DIS	0.00	0.79	0.00
	SEP	0.26	0.79	0.33
INT	**SRD**	0.68	1.00	0.68
	MA	0.53	1.00	0.53
	RA	1.00	1.00	1.00
	FA	0.74	1.00	0.74

Table B.2 Predecessor Scores in Phase 1 (Continued)

Activity (i)	Candidate Predecessors for Activity i (k):	Weighted Predecessor Score (WPSik)	WASi	WPSik / WASi
	SS	0.50	1.00	0.50
	AD	0.79	1.00	0.79
	VER	0.00	1.00	0.00
	VAL	0.00	1.00	0.00
	OP	0.00	1.00	0.00
	MAINT	0.00	1.00	0.00
	DIS	0.00	1.00	0.00
	SEP	0.26	1.00	0.26
VER	**SRD**	0.68	1.00	0.68
	MA	0.53	1.00	0.53
	RA	1.00	1.00	1.00
	FA	0.74	1.00	0.74
	SS	0.50	1.00	0.50
	AD	0.79	1.00	0.79
	INT	1.00	1.00	1.00
	VAL	0.00	1.00	0.00
	OP	0.00	1.00	0.00
	MAINT	0.00	1.00	0.00
	DIS	0.00	1.00	0.00
	SEP	0.38	1.00	0.38
VAL	**SRD**	0.53	0.85	0.62
	MA	0.38	0.85	0.45
	RA	0.85	0.85	1.00
	FA	0.59	0.85	0.69
	SS	0.35	0.85	0.41
	AD	0.65	0.85	0.76
	INT	0.85	0.85	1.00
	VER	0.59	0.85	0.69
	OP	0.00	0.85	0.00
	MAINT	0.00	0.85	0.00
	DIS	0.00	0.85	0.00
	SEP	0.32	0.85	0.38
OP	**SRD**	0.53	0.59	0.90
	MA	0.24	0.59	0.40
	RA	0.59	0.59	1.00
	FA	0.32	0.59	0.55
	SS	0.24	0.59	0.40
	AD	0.41	0.59	0.70
	INT	0.59	0.59	1.00
	VER	0.50	0.59	0.85
	VAL	0.32	0.59	0.55

Table B.2 Predecessor Scores in Phase 1 (Continued)

Activity (i)	Candidate Predecessors for Activity i (k):	Weighted Predecessor Score (WPSik)	WASi	WPSik / WASi
	MAINT	0.00	0.59	0.00
	DIS	0.00	0.59	0.00
	SEP	0.09	0.59	0.15
MAINT	**SRD**	0.53	0.68	0.78
	MA	0.21	0.68	0.30
	RA	0.68	0.68	1.00
	FA	0.41	0.68	0.61
	SS	0.18	0.68	0.26
	AD	0.50	0.68	0.74
	INT	0.68	0.68	1.00
	VER	0.59	0.68	0.87
	VAL	0.41	0.68	0.61
	OP	0.18	0.68	0.26
	DIS	0.00	0.68	0.00
	SEP	0.24	0.68	0.35
DIS	**SRD**	0.53	0.68	0.78
	MA	0.21	0.68	0.30
	RA	0.68	0.68	1.00
	FA	0.41	0.68	0.61
	SS	0.18	0.68	0.26
	AD	0.50	0.68	0.74
	INT	0.68	0.68	1.00
	VER	0.59	0.68	0.87
	VAL	0.68	0.68	1.00
	OP	0.53	0.68	0.78
	MAINT	0.68	0.68	1.00
	SEP	0.31	0.68	0.46
SEP	**SRD**	0.09	0.90	0.10
	MA	0.00	0.90	0.00
	RA	0.00	0.90	0.00
	FA	0.00	0.90	0.00
	SS	0.00	0.90	0.00
	AD	0.00	0.90	0.00
	INT	0.00	0.90	0.00
	VER	0.00	0.90	0.00
	VAL	0.00	0.90	0.00
	OP	0.00	0.90	0.00
	MAINT	0.00	0.90	0.00
	DIS	0.00	0.90	0.00

Table B.3 Predecessor Selection in Phase 2

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	1	2	3	4	5	6	7	8	9	10
SRD	SRD1	SRD2	0	0	0	0	0	0	0	0	0	1
		SRD3	0	0	0	0	0	0	0	0	0	0
	SRD2	SRD1	1	0	1	1	0	1	1	1	1	0
		SRD3	0	0	0	0	0	0	0	0	0	0
	SRD3	SRD1	1	1	1	1	1	1	1	1	1	0
		SRD2	1	1	1	1	1	1	1	1	0	0
MA	MA1	MA2	0	0	0	0	1	0	0	0	0	1
		MA3	0	0	0	0	0	0	0	0	0	1
	MA2	MA1	1	1	0	1	0	0	1	1	1	0
		MA3	0	0	0	0	0	0	0	0	0	0
	MA3	MA1	1	1	0	1	1	1	1	1	1	0
		MA2	1	1	0	1	1	1	1	1	0	1
RA	RA3	RA4	0	0	0	0	0	0	0	0	0	0
		RA5	0	0	0	0	0	0	0	0	0	0
	RA4	RA3	0	0	0	1	0	0	1	0	0	1
		RA5	0	0	0	0	0	0	0	0	0	0
	RA5	RA3	0	1	0	1	0	1	1	0	0	1
		RA4	0	1	0	1	0	1	1	0	0	1
FA	FA1	FA2	0	0	0	0	0	0	0	0	0	0
	FA2	FA1	1	1	1	1	1	1	1	1	1	1
SS	SS1	SS2	0	0	0	0	0	1	0	1	0	0
	SS2	SS1	1	0	0	1	1	0	1	0	0	1
AD	AD1	AD2	0	0	0	0	0	0	0	0	0	0
		AD3	0	0	0	0	0	0	0	0	0	0
	AD2	AD1	1	1	1	1	1	1	1	1	0	1
		AD3	0	0	0	0	0	0	0	0	0	0
	AD3	AD1	1	1	1	1	1	1	1	1	1	0
		AD2	1	0	0	1	1	0	0	1	1	0

Table B.3 Predecessor Selection in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	1	2	3	4	5	6	7	8	9	10
INT	INT1	INT2	0	0	0	0	0	0	0	0	0	0
		INT3	0	0	0	0	0	0	0	0	0	0
		INT4	0	0	0	0	0	0	0	0	0	0
		INT5	0	0	0	0	0	0	0	0	0	0
		INT6	0	0	0	0	0	0	0	0	0	0
		INT7	0	0	0	0	0	0	0	0	0	0
	INT2	INT1	1	0	1	1	0	1	1	1	0	0
		INT3	0	0	0	0	0	0	0	0	0	0
		INT4	0	0	0	0	0	0	0	0	0	0
		INT5	0	0	0	0	0	0	0	0	0	0
		INT6	0	0	0	0	0	0	0	0	0	0
		INT7	0	0	0	0	0	0	0	0	0	0
	INT3	INT1	1	0	1	1	1	1	1	1	1	1
		INT2	1	0	1	1	1	1	1	1	1	1
		INT4	1	0	0	0	1	0	0	1	1	0
		INT5	1	0	0	0	0	0	0	1	0	0
		INT6	0	0	0	0	0	0	0	1	0	0
		INT7	0	0	0	0	0	0	0	1	1	0
	INT4	INT1	1	0	1	1	1	1	1	1	1	1
		INT2	1	0	1	1	1	1	1	1	1	1
		INT3	0	0	1	1	0	1	1	0	0	1
		INT5	0	0	0	0	0	0	0	0	0	0
		INT6	0	0	0	0	0	0	0	0	0	0
		INT7	0	0	0	0	0	0	0	0	0	0
	INT5	INT1	1	0	1	1	1	1	1	1	1	1
		INT2	1	0	1	1	1	1	1	1	1	1
		INT3	0	0	0	1	1	1	1	0	0	1
		INT4	0	0	0	1	1	1	0	1	1	0
		INT6	0	0	0	0	0	0	0	0	0	0
		INT7	0	0	0	0	0	0	0	0	1	0
	INT6	INT1	1	0	1	1	1	1	1	1	1	1
		INT2	1	0	1	1	1	1	1	1	1	1
		INT3	1	0	1	1	1	1	1	0	1	1
		INT4	1	0	1	1	1	1	1	0	1	1
		INT5	1	0	1	1	0	1	1	0	1	1
		INT7	0	0	0	0	0	0	0	0	1	0
	INT7	INT1	1	0	1	1	1	1	1	1	1	1
		INT2	1	0	1	1	1	1	0	0	1	1
		INT3	1	0	0	1	1	1	0	0	0	0
		INT4	1	0	0	1	1	1	0	0	0	0

Table B.3 Predecessor Selection in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	1	2	3	4	5	6	7	8	9	10
		INT5	1	0	0	1	0	1	0	0	0	0
		INT6	1	0	0	1	0	1	0	0	0	0
VER	VER1	VER2	0	0	0	0	0	0	0	0	0	0
		VER3	0	0	0	0	0	0	0	0	0	0
		VER4	0	0	0	0	0	0	0	0	0	0
	VER2	VER1	1	0	1	1	1	1	1	1	1	1
		VER3	0	0	0	0	0	0	0	0	0	0
		VER4	0	0	0	0	0	0	0	0	0	0
	VER3	VER1	1	1	1	1	1	1	1	1	1	1
		VER2	1	1	1	1	0	1	1	1	1	1
		VER4	0	0	0	0	0	0	0	0	1	0
	VER4	VER1	1	1	1	1	1	1	1	1	1	1
		VER2	1	1	1	1	0	1	1	1	0	1
		VER3	1	1	1	0	0	1	1	0	0	1
VAL	VAL1	VAL2	0	0	0	0	0	0	0	0	0	0
		VAL3	0	0	0	0	0	0	0	0	0	0
		VAL4	0	0	0	0	0	0	0	0	0	0
		VAL5	0	0	0	0	0	0	0	0	0	0
		VAL6	0	0	0	0	0	0	0	0	0	0
		VAL7	0	0	0	0	0	0	0	0	0	0
		VAL8	0	0	0	0	0	0	0	0	0	0
	VAL2	VAL1	1	0	1	1	1	1	1	1	1	1
		VAL3	0	0	0	0	0	0	0	0	0	0
		VAL4	0	0	0	0	0	0	0	0	0	0
		VAL5	0	0	0	0	0	0	0	0	0	0
		VAL6	0	0	0	0	0	0	0	0	0	0
		VAL7	0	0	0	0	0	0	0	0	0	0
		VAL8	0	0	0	0	0	0	0	0	0	0
	VAL3	VAL1	1	1	1	1	1	1	1	1	1	1
		VAL2	1	1	1	1	1	1	1	1	0	0
		VAL4	1	0	0	0	0	0	0	0	0	0
		VAL5	0	0	0	0	0	0	0	0	0	0
		VAL6	0	0	0	0	0	0	0	0	0	0
		VAL7	0	0	0	0	0	0	0	0	0	0
		VAL8	0	0	0	0	0	0	0	0	0	0
	VAL4	VAL1	1	1	1	1	0	1	1	1	1	1
		VAL2	0	1	1	0	0	1	1	0	1	1
		VAL3	0	1	1	0	0	1	1	0	1	1
		VAL5	0	0	0	0	0	0	0	0	1	0
		VAL6	0	0	0	0	0	0	0	0	0	0

Table B.3 Predecessor Selection in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	1	2	3	4	5	6	7	8	9	10
		VAL7	0	0	0	0	0	0	0	0	0	0
		VAL8	0	0	0	0	0	0	0	0	0	0
	VAL5	VAL1	1	1	1	1	1	1	1	1	1	1
		VAL2	1	1	1	1	1	1	1	1	0	1
		VAL3	1	1	1	1	1	1	1	1	0	1
		VAL4	1	0	0	0	0	1	0	0	0	0
		VAL6	0	0	0	0	0	0	0	0	0	0
		VAL7	0	0	0	0	0	0	0	0	0	0
		VAL8	0	0	0	0	0	0	0	0	0	0
	VAL6	VAL1	1	1	1	1	1	1	1	1	1	1
		VAL2	1	1	1	1	1	1	1	1	1	1
		VAL3	1	1	1	1	1	1	1	1	1	1
		VAL4	1	0	1	1	0	1	1	0	0	1
		VAL5	1	0	1	1	0	1	1	0	1	1
		VAL7	0	0	0	0	0	0	0	0	0	0
		VAL8	0	0	0	0	0	0	0	0	0	0
	VAL7	VAL1	1	1	1	1	1	1	1	1	1	1
		VAL2	1	1	1	1	1	1	1	1	1	1
		VAL3	1	1	1	1	1	1	1	1	1	1
		VAL4	1	1	1	1	0	1	1	0	1	1
		VAL5	1	1	1	1	0	1	1	0	1	1
		VAL6	0	1	1	1	0	1	0	0	1	1
		VAL8	0	0	0	0	0	0	0	0	0	0
	VAL8	VAL1	1	1	1	1	1	1	1	1	1	1
		VAL2	1	1	1	1	1	1	1	1	0	1
		VAL3	1	1	1	1	1	1	1	1	0	1
		VAL4	1	1	1	1	0	1	1	1	0	1
		VAL5	1	1	1	1	1	1	1	1	0	1
		VAL6	1	1	1	1	1	1	1	1	0	1
		VAL7	1	0	1	1	1	1	1	1	0	1
MAINT	MAINT1	MAINT2	0	0	0	0	0	0	0	0	0	0
		MAINT3	0	0	0	0	0	0	0	0	0	0
		MAINT4	0	0	0	0	0	0	0	0	0	0
		MAINT5	0	0	0	0	0	0	0	0	0	0
		MAINT6	0	0	0	0	0	0	0	0	0	0
		MAINT7	0	0	0	0	0	0	0	0	0	0
		MAINT8	0	0	0	0	0	0	0	0	0	0
	MAINT2	MAINT1	1	1	1	1	1	1	1	1	0	1
		MAINT3	0	0	0	0	0	0	0	0	0	0
		MAINT4	0	0	0	0	0	0	0	0	0	0

Table B.3 Predecessor Selection in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	1	2	3	4	5	6	7	8	9	10
		MAINT5	0	0	0	0	0	0	0	0	0	0
		MAINT6	0	0	0	0	0	0	0	0	0	0
		MAINT7	0	0	0	0	0	0	0	0	0	0
		MAINT8	0	0	0	0	0	0	0	0	0	0
	MAINT3	**MAINT1**	1	1	1	1	1	1	1	1	0	1
		MAINT2	1	0	1	1	1	0	0	1	1	1
		MAINT4	0	0	0	0	0	0	0	0	0	0
		MAINT5	0	0	0	0	0	0	0	0	0	0
		MAINT6	0	0	0	0	0	0	0	0	0	0
		MAINT7	0	0	0	0	0	0	0	0	0	0
		MAINT8	0	0	0	0	0	0	0	0	0	0
	MAINT4	**MAINT1**	1	1	1	1	1	1	1	1	0	1
		MAINT2	1	1	1	1	1	0	1	1	1	1
		MAINT3	0	1	1	1	1	0	1	1	1	1
		MAINT5	0	0	0	0	0	0	0	0	0	0
		MAINT6	0	0	0	0	0	0	0	0	0	0
		MAINT7	0	0	0	0	0	0	0	0	0	0
		MAINT8	0	0	0	0	0	0	0	0	0	0
	MAINT5	**MAINT1**	1	1	1	1	1	1	1	1	0	1
		MAINT2	1	1	1	0	1	0	1	1	1	1
		MAINT3	0	1	1	0	1	0	1	0	1	1
		MAINT4	0	1	0	0	0	0	0	0	0	0
		MAINT6	0	0	0	0	0	0	0	0	0	0
		MAINT7	0	0	0	0	0	0	0	0	0	0
		MAINT8	0	0	0	0	0	0	0	0	0	0
	MAINT6	**MAINT1**	1	1	1	1	1	1	1	1	1	1
		MAINT2	1	1	1	1	1	1	1	1	1	1
		MAINT3	1	1	1	1	1	1	1	1	1	1
		MAINT4	1	1	1	1	1	1	1	0	1	0
		MAINT5	1	1	1	0	1	1	1	0	1	0
		MAINT7	0	0	0	0	0	0	0	0	0	0
		MAINT8	0	0	0	0	0	0	0	0	0	0
	MAINT7	**MAINT1**	1	1	1	1	1	1	1	1	1	1
		MAINT2	1	1	1	1	1	1	1	1	1	1
		MAINT3	1	1	1	1	1	1	1	0	1	1
		MAINT4	1	1	1	1	1	1	1	0	1	0
		MAINT5	1	1	1	1	1	1	1	0	1	0
		MAINT6	0	1	0	1	0	1	0	0	0	0
		MAINT8	0	0	0	1	0	0	0	0	0	0
	MAINT8	**MAINT1**	1	1	1	1	1	1	1	1	1	1

Table B.3 Predecessor Selection in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	1	2	3	4	5	6	7	8	9	10
		MAINT2	1	1	1	0	1	1	1	1	1	1
		MAINT3	1	1	1	0	1	1	1	1	1	1
		MAINT4	1	1	1	0	1	1	1	1	1	0
		MAINT5	1	1	1	0	1	1	1	1	1	0
		MAINT6	1	1	0	0	0	1	0	1	0	0
		MAINT7	1	0	0	0	0	1	0	1	0	0
OP	OP1	OP2	0	0	0	0	0	0	0	0	0	0
		OP3	0	0	0	0	0	0	0	0	0	0
		OP4	0	0	0	0	0	0	0	0	0	0
		OP5	0	0	0	0	0	0	0	0	0	0
	OP2	OP1	1	1	1	1	1	1	1	1	1	1
		OP3	0	0	0	0	0	0	0	0	0	0
		OP4	0	0	0	0	0	0	0	0	0	0
		OP5	0	0	0	0	0	0	0	0	0	0
	OP3	OP1	1	1	1	1	1	1	1	1	1	1
		OP2	1	0	1	1	1	1	1	1	0	1
		OP4	0	0	0	0	0	0	0	0	0	0
		OP5	0	0	0	0	0	0	0	0	0	0
	OP4	OP1	1	1	1	1	1	1	1	1	1	1
		OP2	1	1	1	1	1	1	1	1	0	1
		OP3	1	0	0	1	1	0	0	0	0	1
		OP5	0	0	0	0	0	0	0	0	0	0
	OP5	OP1	1	1	1	1	1	1	1	1	1	1
		OP2	1	0	1	0	1	1	1	0	1	1
		OP3	1	1	0	0	1	1	0	0	1	1
		OP4	1	0	0	0	0	1	0	0	1	1
DIS	DIS1	DIS2	0	0	0	0	0	1	0	0	0	0
		DIS3	0	0	0	0	0	1	0	0	0	0
		DIS4	0	0	0	0	0	0	0	0	0	0
		DIS5	0	0	0	0	0	0	0	0	0	0
		DIS6	0	0	0	0	0	0	0	0	0	0
		DIS7	0	0	0	0	0	0	0	0	0	0
	DIS2	DIS1	0	1	1	1	0	0	1	1	0	1
		DIS3	0	0	0	0	0	1	0	0	0	0
		DIS4	0	0	0	0	0	0	0	0	0	0
		DIS5	0	0	0	0	0	0	0	0	0	0
		DIS6	0	0	0	0	0	0	0	0	0	0
		DIS7	0	0	0	0	0	0	0	0		0
	DIS3	DIS1	1	1	1	1	1	0	1	1	1	1
		DIS2	1	0	0	1	1	0	1	1	0	0

Table B.3 Predecessor Selection in Phase 2 (Continued)

Activity (i)	**Subactivity (n)**	**Candidate Predecessors for Each Subactivity (k)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
		DIS4	0	0	0	0	0	0	0	0	0	0
		DIS5	0	0	0	0	0	0	0	0	0	0
		DIS6	0	0	0	0	0	0	0	0	0	0
		DIS7	0	0	0	0	0	0	0	0	0	0
	DIS4	**DIS1**	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS2	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS3	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS5	0	0	0	0	0	**1**	0	0	0	0
		DIS6	0	0	0	0	0	**1**	0	0	0	0
		DIS7	0	0	0	0	0	0	0	0	0	0
	DIS5	**DIS1**	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS2	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS3	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS4	0	0	**1**	**1**	0	0	**1**	**1**	0	**1**
		DIS6	0	0	0	0	0	0	0	0	0	0
		DIS7	0	0	0	0	0	0	0	0	0	0
	DIS6	**DIS1**	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS2	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS3	**1**	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS4	**1**	1	**1**	**1**	0	0	**1**	**1**	**1**	**1**
		DIS5	**1**	1	**1**	**1**	0	0	**1**	0	**1**	**1**
		DIS7	0	0	0	0	0	0	0	0	0	0
	DIS7	**DIS1**	**1**	1	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**
		DIS2	**1**	1	0	**1**	**1**	**1**	0	**1**	**1**	**1**
		DIS3	**1**	1	0	**1**	**1**	**1**	0	**1**	**1**	**1**
		DIS4	**1**	1	0	0	**1**	**1**	0	0	**1**	**1**
		DIS5	**1**	1	0	0	**1**	**1**	0	0	**1**	0
		DIS6	**1**	1	0	0	**1**	**1**	0	0	**1**	0
SEP	**SEP1**	**SEP2**	0	0	0	0	0	0	0	0	0	0
	SEP2	**SEP1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	0	**1**

Table B.4 Predecessor Scores in Phase 2

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
SRD	SRD1	SRD2	0.23	1.00	0.23
		SRD3	0.00	1.00	0.00
	SRD2	SRD1	0.72	1.00	0.72
		SRD3	0.00	1.00	0.00
	SRD3	SRD1	0.77	1.00	0.77
		SRD2	0.69	1.00	0.69
MA	MA1	MA2	0.26	1.00	0.26
		MA3	0.23	1.00	0.23
	MA2	MA1	0.54	1.00	0.54
		MA3	0.00	1.00	0.00
	MA3	MA1	0.64	1.00	0.64
		MA2	0.79	1.00	0.79
RA	RA3	RA4	0.00	0.59	0.00
		RA5	0.00	0.59	0.00
	RA4	RA3	0.51	0.59	0.87
		RA5	0.00	0.59	0.00
	RA5	RA3	0.62	0.59	1.04
		RA4	0.62	0.59	1.04
FA	FA1	FA2	0.00	1.00	0.00
	FA2	FA1	1.00	1.00	1.00
SS	SS1	SS2	0.21	1.00	0.21
	SS2	SS1	0.56	1.00	0.56
AD	AD1	AD2	0.00	1.00	0.00
		AD3	0.00	1.00	0.00
	AD2	AD1	0.92	1.00	0.92
		AD3	0.00	1.00	0.00
	AD3	AD1	0.77	1.00	0.77
		AD2	0.46	1.00	0.46

Table B.4 Predecessor Scores in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
INT	INT1	INT2	0.00	0.97	0.00
		INT3	0.00	0.97	0.00
		INT4	0.00	0.97	0.00
		INT5	0.00	0.97	0.00
		INT6	0.00	0.97	0.00
		INT7	0.00	0.97	0.00
	INT2	INT1	0.64	0.97	0.66
		INT3	0.00	0.97	0.00
		INT4	0.00	0.97	0.00
		INT5	0.00	0.97	0.00
		INT6	0.00	0.97	0.00
		INT7	0.00	0.97	0.00
	INT3	INT1	0.97	0.97	1.00
		INT2	0.97	0.97	1.00
		INT4	0.26	0.97	0.26
		INT5	0.15	0.97	0.16
		INT6	0.13	0.97	0.13
		INT7	0.21	0.97	0.21
	INT4	INT1	0.97	0.97	1.00
		INT2	0.97	0.97	1.00
		INT3	0.72	0.97	0.74
		INT5	0.00	0.97	0.00
		INT6	0.00	0.97	0.00
		INT7	0.00	0.97	0.00
	INT5	INT1	0.97	0.97	1.00
		INT2	0.97	0.97	1.00
		INT3	0.62	0.97	0.63
		INT4	0.51	0.97	0.53
		INT6	0.00	0.97	0.00
		INT7	0.08	0.97	0.08
	INT6	INT1	0.97	0.97	1.00
		INT2	0.97	0.97	1.00
		INT3	0.85	0.97	0.87
		INT4	0.85	0.97	0.87
		INT5	0.82	0.97	0.84
		INT7	0.08	0.97	0.08
	INT7	INT1	0.97	0.97	1.00

Table B.4 Predecessor Scores in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
		INT2	0.77	0.97	0.79
		INT3	0.33	0.97	0.34
		INT4	0.33	0.97	0.34
		INT5	0.31	0.97	0.32
		INT6	0.31	0.97	0.32
VER	VER1	VER2	0.00	1.00	0.00
		VER3	0.00	1.00	0.00
		VER4	0.00	1.00	0.00
	VER2	VER1	0.97	1.00	0.97
		VER3	0.00	1.00	0.00
		VER4	0.00	1.00	0.00
	VER3	VER1	1.00	1.00	1.00
		VER2	0.97	1.00	0.97
		VER4	0.08	1.00	0.08
	VER4	VER1	1.00	1.00	1.00
		VER2	0.90	1.00	0.90
		VER3	0.56	1.00	0.56
VAL	VAL1	VAL2	0.00	1.00	0.00
		VAL3	0.00	1.00	0.00
		VAL4	0.00	1.00	0.00
		VAL5	0.00	1.00	0.00
		VAL6	0.00	1.00	0.00
		VAL7	0.00	1.00	0.00
		VAL8	0.00	1.00	0.00
	VAL2	VAL1	0.97	1.00	0.97
		VAL3	0.00	1.00	0.00
		VAL4	0.00	1.00	0.00
		VAL5	0.00	1.00	0.00
		VAL6	0.00	1.00	0.00
		VAL7	0.00	1.00	0.00
		VAL8	0.00	1.00	0.00
	VAL3	VAL1	1.00	1.00	1.00
		VAL2	0.69	1.00	0.69
		VAL4	0.03	1.00	0.03
		VAL5	0.00	1.00	0.00
		VAL6	0.00	1.00	0.00
		VAL7	0.00	1.00	0.00

Table B.4 Predecessor Scores in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
		VAL8	0.00	1.00	0.00
	VAL4	VAL1	0.97	1.00	0.97
		VAL2	0.62	1.00	0.62
		VAL3	0.62	1.00	0.62
		VAL5	0.08	1.00	0.08
		VAL6	0.00	1.00	0.00
		VAL7	0.00	1.00	0.00
		VAL8	0.00	1.00	0.00
	VAL5	VAL1	1.00	1.00	1.00
		VAL2	0.92	1.00	0.92
		VAL3	0.92	1.00	0.92
		VAL4	0.10	1.00	0.10
		VAL6	0.00	1.00	0.00
		VAL7	0.00	1.00	0.00
		VAL8	0.00	1.00	0.00
	VAL6	VAL1	1.00	1.00	1.00
		VAL2	1.00	1.00	1.00
		VAL3	1.00	1.00	1.00
		VAL4	0.74	1.00	0.74
		VAL5	0.82	1.00	0.82
		VAL7	0.00	1.00	0.00
		VAL8	0.00	1.00	0.00
	VAL7	VAL1	1.00	1.00	1.00
		VAL2	1.00	1.00	1.00
		VAL3	1.00	1.00	1.00
		VAL4	0.85	1.00	0.85
		VAL5	0.85	1.00	0.85
		VAL6	0.74	1.00	0.74
		VAL8	0.00	1.00	0.00
	VAL8	VAL1	1.00	1.00	1.00
		VAL2	0.92	1.00	0.92
		VAL3	0.92	1.00	0.92
		VAL4	0.90	1.00	0.90
		VAL5	0.92	1.00	0.92
		VAL6	0.92	1.00	0.92
		VAL7	0.90	1.00	0.90
MAINT	MAINT1	MAINT2	0.00	1.00	0.00

Table B.4 Predecessor Scores in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
		MAINT3	0.00	1.00	0.00
		MAINT4	0.00	1.00	0.00
		MAINT5	0.00	1.00	0.00
		MAINT6	0.00	1.00	0.00
		MAINT7	0.00	1.00	0.00
		MAINT8	0.00	1.00	0.00
	MAINT2	**MAINT1**	0.92	1.00	0.92
		MAINT3	0.00	1.00	0.00
		MAINT4	0.00	1.00	0.00
		MAINT5	0.00	1.00	0.00
		MAINT6	0.00	1.00	0.00
		MAINT7	0.00	1.00	0.00
		MAINT8	0.00	1.00	0.00
	MAINT3	**MAINT1**	0.92	1.00	0.92
		MAINT2	0.82	1.00	0.82
		MAINT4	0.00	1.00	0.00
		MAINT5	0.00	1.00	0.00
		MAINT6	0.00	1.00	0.00
		MAINT7	0.00	1.00	0.00
		MAINT8	0.00	1.00	0.00
	MAINT4	**MAINT1**	0.92	1.00	0.92
		MAINT2	0.92	1.00	0.92
		MAINT3	0.90	1.00	0.90
		MAINT5	0.00	1.00	0.00
		MAINT6	0.00	1.00	0.00
		MAINT7	0.00	1.00	0.00
		MAINT8	0.00	1.00	0.00
	MAINT5	**MAINT1**	0.92	1.00	0.92
		MAINT2	0.72	1.00	0.72
		MAINT3	0.56	1.00	0.56
		MAINT4	0.03	1.00	0.03
		MAINT6	0.00	1.00	0.00
		MAINT7	0.00	1.00	0.00
		MAINT8	0.00	1.00	0.00
	MAINT6	**MAINT1**	1.00	1.00	1.00
		MAINT2	1.00	1.00	1.00
		MAINT3	1.00	1.00	1.00

Table B.4 Predecessor Scores in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
		MAINT4	0.64	1.00	0.64
		MAINT5	0.44	1.00	0.44
		MAINT7	0.00	1.00	0.00
		MAINT8	0.00	1.00	0.00
	MAINT7	**MAINT1**	1.00	1.00	1.00
		MAINT2	1.00	1.00	1.00
		MAINT3	0.87	1.00	0.87
		MAINT4	0.64	1.00	0.64
		MAINT5	0.64	1.00	0.64
		MAINT6	0.31	1.00	0.31
		MAINT8	0.21	1.00	0.21
	MAINT8	**MAINT1**	1.00	1.00	1.00
		MAINT2	0.79	1.00	0.79
		MAINT3	0.79	1.00	0.79
		MAINT4	0.56	1.00	0.56
		MAINT5	0.56	1.00	0.56
		MAINT6	0.26	1.00	0.26
		MAINT7	0.23	1.00	0.23
OP	**OP1**	**OP2**	0.00	1.00	0.00
		OP3	0.00	1.00	0.00
		OP4	0.00	1.00	0.00
		OP5	0.00	1.00	0.00
	OP2	**OP1**	1.00	1.00	1.00
		OP3	0.00	1.00	0.00
		OP4	0.00	1.00	0.00
		OP5	0.00	1.00	0.00
	OP3	**OP1**	1.00	1.00	1.00
		OP2	0.90	1.00	0.90
		OP4	0.00	1.00	0.00
		OP5	0.00	1.00	0.00
	OP4	**OP1**	1.00	1.00	1.00
		OP2	0.92	1.00	0.92
		OP3	0.49	1.00	0.49
		OP5	0.00	1.00	0.00
	OP5	**OP1**	1.00	1.00	1.00
		OP2	0.64	1.00	0.64
		OP3	0.46	1.00	0.46

Table B.4 Predecessor Scores in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
		OP4	0.41	1.00	0.41
DIS	**DIS1**	**DIS2**	0.08	1.00	0.08
		DIS3	0.08	1.00	0.08
		DIS4	0.00	1.00	0.00
		DIS5	0.00	1.00	0.00
		DIS6	0.00	1.00	0.00
		DIS7	0.00	1.00	0.00
	DIS2	**DIS1**	0.79	1.00	0.79
		DIS3	0.08	1.00	0.08
		DIS4	0.00	1.00	0.00
		DIS5	0.00	1.00	0.00
		DIS6	0.00	1.00	0.00
		DIS7	0.00	1.00	0.00
	DIS3	**DIS1**	0.92	1.00	0.92
		DIS2	0.46	1.00	0.46
		DIS4	0.00	1.00	0.00
		DIS5	0.00	1.00	0.00
		DIS6	0.00	1.00	0.00
		DIS7	0.00	1.00	0.00
	DIS4	**DIS1**	1.00	1.00	1.00
		DIS2	1.00	1.00	1.00
		DIS3	0.97	1.00	0.97
		DIS5	0.08	1.00	0.08
		DIS6	0.08	1.00	0.08
		DIS7	0.00	1.00	0.00
	DIS5	**DIS1**	1.00	1.00	1.00
		DIS2	0.97	1.00	0.97
		DIS3	1.00	1.00	1.00
		DIS4	0.77	1.00	0.77
		DIS6	0.00	1.00	0.00
		DIS7	0.00	1.00	0.00
	DIS6	**DIS1**	1.00	1.00	1.00
		DIS2	1.00	1.00	1.00
		DIS3	1.00	1.00	1.00
		DIS4	0.90	1.00	0.90
		DIS5	0.77	1.00	0.77
		DIS7	0.00	1.00	0.00

Table B.4 Predecessor Scores in Phase 2 (Continued)

Activity (i)	Subactivity (n)	Candidate Predecessors for Each Subactivity (k)	Weighted Predecessor Score (WPSink)	WASin	WPSink / WASin
	DIS7	**DIS1**	0.87	1.00	0.87
		DIS2	0.79	1.00	0.79
		DIS3	0.79	1.00	0.79
		DIS4	0.46	1.00	0.46
		DIS5	0.23	1.00	0.23
		DIS6	0.23	1.00	0.23
SEP	**SEP1**	**SEP2**	0.00	1.00	0.00
	SEP2	**SEP1**	0.90	1.00	0.90

APPENDIX C

SECOND LEVEL ACTIVITY NETWORKS

Figure C.1 Second Level Activity Network for SRD

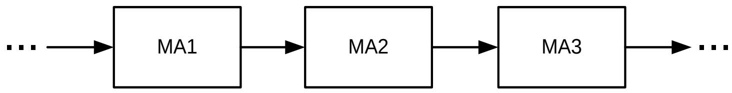


Figure C.2 Second Level Activity Network for MA

Figure C.3 Second Level Activity Network for RA

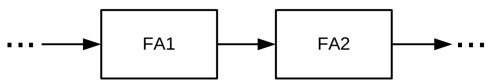


Figure C.4 Second Level Activity Network for FA

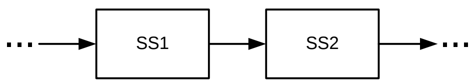


Figure C.5 Second Level Activity Network for SS

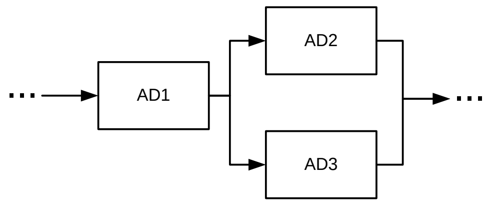


Figure C.6 Second Level Activity Network for AD

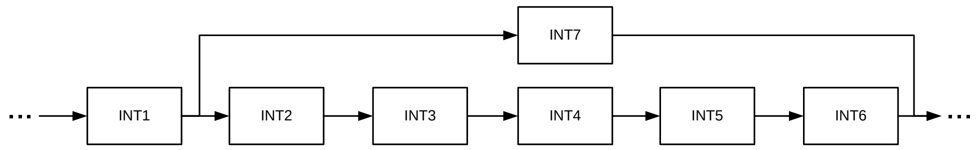


Figure C.7 Second Level Activity Network for INT

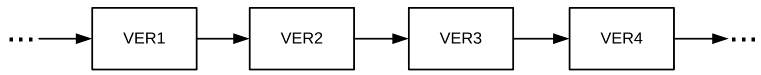


Figure C.8 Second Level Activity Network for VER

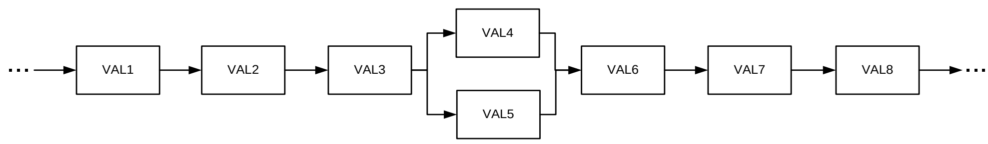


Figure C.9 Second Level Activity Network for VAL

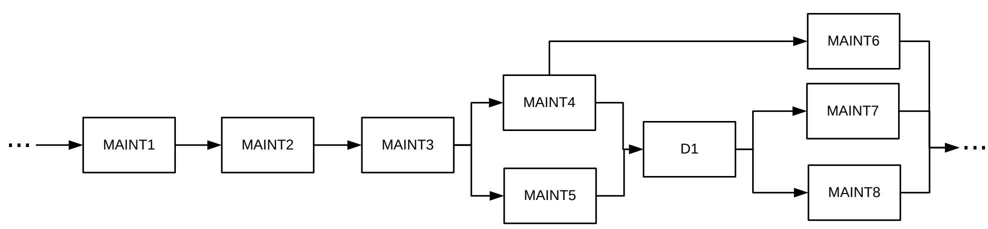


Figure C.10 Second Level Activity Network for MAINT

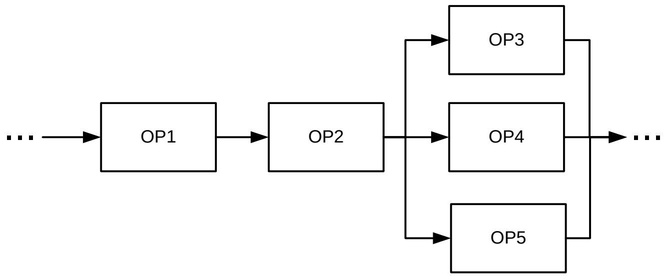


Figure C.11 Second Level Activity Network for OP

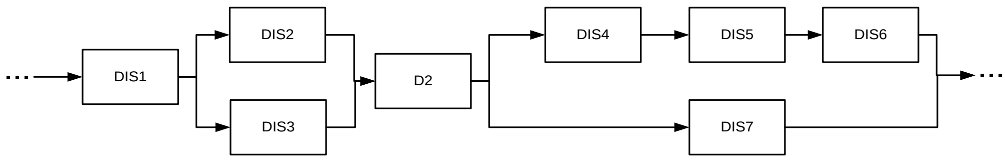


Figure C.12 Second Level Activity Network for DIS

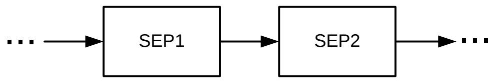


Figure C.13 Second Level Activity Network for SEP

APPENDIX D

VBA CODES FOR MODEL TRANSFORMATION

D.1 REARRANGE VBA CODE

```
Sub Rearrange()

Dim wbk As Workbook

FirstFile = "C:\Users\Merve\Desktop\Macros_Final\Rhapsody_Output.xlsm"

SecondFile = "C:\Users\Merve\Desktop\Macros_Final\Transfer_to_Arena.xls"

Set wbk = Workbooks.Open(FirstFile)

Set wbk = Workbooks.Open(SecondFile)

Set wbk = Workbooks("Rhapsody_Output.xlsm")

wbk.Sheets("Sheet1").Range("B2").Copy

Set wbk = Workbooks("Transfer_to_Arena.xls")

wbk.Sheets("Elements_Resources_Resources").Range("M3").PasteSpecial Paste:=xlPasteAll,
Operation:=xlNone, SkipBlanks:= _

    False, Transpose:=False

Set wbk = Workbooks("Rhapsody_Output.xlsm")

wbk.Sheets("Sheet1").Range("B3").Copy

Set wbk = Workbooks("Transfer_to_Arena.xls")

wbk.Sheets("Elements_Resources_Resources").Range("M2").PasteSpecial Paste:=xlPasteAll,
Operation:=xlNone, SkipBlanks:= _

    False, Transpose:=False

Set wbk = Workbooks("Rhapsody_Output.xlsm")

wbk.Sheets("Sheet1").Range("B4").Copy

Set wbk = Workbooks("Transfer_to_Arena.xls")

wbk.Sheets("Elements_Resources_Resources").Range("M4").PasteSpecial Paste:=xlPasteAll,
Operation:=xlNone, SkipBlanks:= _
```

```
        False, Transpose:=False
wbk.Save
wbk.Close
Set wbk = Workbooks("Rhapsody_Output.xlsm")
wbk.Sheets("Sheet1").Range("B2:B4").Select
Selection.EntireRow.Delete
    Dim objRange As Range
    Set objRange = Range("B4:B100")
    objRange.TextToColumns _
      Destination:=Range("C4"), _
      DataType:=xlDelimited, _
      TextQualifier:=xlDoubleQuote, _
      ConsecutiveDelimiter:=False, _
      Tab:=False, _
      Semicolon:=False, _
      Comma:=False, _
      Space:=True, _
      Other:=False, _
      OtherChar:="-"
          Range("B1:B100").Select
    Selection.SpecialCells(xlCellTypeBlanks).Select
    Selection.EntireRow.Delete
    Range("G2").Select
    ActiveCell.FormulaR1C1 = _
        "=RIGHT(RC[-4],(LEN(RC[-4])-(SEARCH(""."",RC[-4],1))))"
    Range("H2").Select
    ActiveCell.FormulaR1C1 = _
        "=RIGHT(RC[-4],(LEN(RC[-4])-(SEARCH(""."",RC[-4],1))))"
    Range("I2").Select
    ActiveCell.FormulaR1C1 = _
        "=RIGHT(RC[-4],(LEN(RC[-4])-(SEARCH(""."",RC[-4],1))))"
    Range("J2").Select
```

```
    ActiveCell.FormulaR1C1 = _
        "=RIGHT(RC[-4],(LEN(RC[-4])-(SEARCH("":"",RC[-4],1))))"
    Range("G2:J2").Select
    Selection.AutoFill Destination:=Range("G2:J58"), Type:=xlFillDefault
    Range("G2:J58").Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
Range("C1:F1").Select
Selection.EntireColumn.Delete
Range("C1:F1").Select
Selection.EntireRow.Delete
ActiveWorkbook.SaveAs "C:\Users\Merve\Desktop\Macros_Final\Rhapsody_Output_2.xlsm",
FileFormat:=52
wbk.Close
End Sub
```

D.2 MACRO TRANSFER 1 VBA CODE

```
Sub COPYCELL()

Dim wbk As Workbook

StrSecondFile = "C:\Users\Merve\Desktop\Macros_Final\Rhapsody_Output_2.xlsm"

StrThirdFile = "C:\Users\Merve\Desktop\Macros_Final\Transfer_to_Arena.xls"

Set wbk = Workbooks.Open(StrSecondFile)

wbk.Sheets("Sheet1").Range("A1:F6").Copy

wbk.Sheets("Sheet1").Range("H1:M6").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _

    False, Transpose:=False

wbk.Sheets("Sheet1").Range("A10:F11").Copy

wbk.Sheets("Sheet1").Range("H7:M8").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _

    False, Transpose:=False

wbk.Sheets("Sheet1").Range("A7:F9").Copy

wbk.Sheets("Sheet1").Range("H9:M11").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _

    False, Transpose:=False

wbk.Sheets("Sheet1").Range("A12:F16").Copy

wbk.Sheets("Sheet1").Range("H12:M16").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _

    False, Transpose:=False

wbk.Sheets("Sheet1").Range("A19:F37").Copy

wbk.Sheets("Sheet1").Range("H17:M35").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _

    False, Transpose:=False

wbk.Sheets("Sheet1").Range("A17:F18").Copy

wbk.Sheets("Sheet1").Range("H36:M37").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _

    False, Transpose:=False

wbk.Sheets("Sheet1").Range("A38:F43").Copy

wbk.Sheets("Sheet1").Range("H38:M43").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _

    False, Transpose:=False

wbk.Sheets("Sheet1").Range("A45:F45").Copy
```

```
wbk.Sheets("Sheet1").Range("H44:M44").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
wbk.Sheets("Sheet1").Range("A44:F44").Copy
wbk.Sheets("Sheet1").Range("H45:M45").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
wbk.Sheets("Sheet1").Range("A46:F48").Copy
wbk.Sheets("Sheet1").Range("H46:M48").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
wbk.Sheets("Sheet1").Range("A50:F50").Copy
wbk.Sheets("Sheet1").Range("H49:M49").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
wbk.Sheets("Sheet1").Range("A49:F49").Copy
wbk.Sheets("Sheet1").Range("H50:M50").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
wbk.Sheets("Sheet1").Range("A51:F57").Copy
wbk.Sheets("Sheet1").Range("H51:M57").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
wbk.Sheets("Sheet1").Range("A1:G1").Select
Selection.EntireColumn.Delete
wbk.Sheets("Sheet1").Range("C1:C57").Copy
Set wbk = Workbooks.Open(StrThirdFile)
wbk.Sheets("Blocks_Delay").Range("I2:I58").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Set wbk = Workbooks("Rhapsody_Output_2.xlsm")
wbk.Sheets("Sheet1").Range("D1").Copy
Set wbk = Workbooks("Transfer_to_Arena.xls")
wbk.Sheets("Blocks_Release_Resources").Range("D4").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
```

```
…*
wbk.Save
wbk.Close
Set wbk = Workbooks("Rhapsody_Output_2.xlsm")
wbk.Save
wbk.Close
End Sub
```

* Here, VBA code continues with copying resources to be released from “Rhapsody_Output_2.xlsm” and pastes them to "Transfer_to_Arena.xls". This part is not included since it is the extension of the above part with no difference in represented functionality.

D.3 MACRO TRANSFER 2 VBA CODE

```
Sub COPYCELL2()

Dim wbk As Workbook

StrSecondFile = "C:\Users\Merve\Desktop\Macros_Final\Rhapsody_Output_2.xlsm"

StrThirdFile = "C:\Users\Merve\Desktop\Macros_Final\Transfer_to_Arena.xls"

Set wbk = Workbooks.Open(StrSecondFile)

Set wbk = Workbooks.Open(StrThirdFile)

Set wbk = Workbooks("Rhapsody_Output_2.xlsm")

wbk.Sheets("Sheet1").Range("D1").Copy

Set wbk = Workbooks("Transfer_to_Arena.xls")

wbk.Sheets("Blocks_Seize_Resources").Range("D4").PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _

    False, Transpose:=False

…*

wbk.Save

wbk.Close

Set wbk = Workbooks("Rhapsody_Output_2.xlsm")

wbk.Save

wbk.Close

End Sub
```

* Here, VBA code continues with copying resources to be seized from “Rhapsody_Output_2.xlsm” and pastes them to "Transfer_to_Arena.xls". This part is not included since it is the extension of the above part with no difference in represented functionality.

APPENDIX E

ACTIVITY RESOURCE REQUIREMENTS AND DURATIONS FOR CASES

Table E.1Activity Resource Requirements and Durations for Deterministic Cases

Activity Code*	Case D1: Small Scale and Low Resource Availability				Case D2: Large Scale and Low Resource Availability				Case D3: Large Scale and High Resource Availability			
	Resources Required			Constant Duration (Work Day)	Resources Required			Constant Duration (Work Day)	Resources Required			Constant Duration (Work Day)
	SysEng	SME	PM		SysEng	SME	PM		SysEng	SME	PM	
SRD1	3	1	1	3	3	1	1	6	3	1	1	6
SRD2	3	1	0	3	3	1	0	6	3	1	0	6
SRD3	4	1	0	4	4	1	0	8	4	1	0	8
MA1	2	1	1	2	2	1	1	4	2	1	1	4
MA2	2	1	1	3	2	1	1	6	2	1	1	6
MA3	2	1	0	2	2	1	0	4	2	1	0	4
RA3	3	1	1	3	3	1	1	6	3	1	1	6
RA4	4	2	0	7	4	2	0	14	4	2	0	14
RA5	3	2	0	5	3	2	0	10	3	2	0	10
FA1	4	5	1	8	4	5	1	16	4	5	1	16
FA2	6	5	0	7	6	5	0	14	6	5	0	14

Table E.1 Activity Resource Requirements and Durations for Deterministic Cases (Continued)

	Case D1: Small Scale and Low Resource Availability				Case D2: Large Scale and Low Resource Availability				Case D3: Large Scale and High Resource Availability			
	Resources Required				Resources Required				Resources Required			
Activity Code*	SysEng	SME	PM	Constant Duration (Work Day)	SysEng	SME	PM	Constant Duration (Work Day)	SysEng	SME	PM	Constant Duration (Work Day)
SS1	4	10	0	10	4	10	0	20	4	10	0	20
SS2	3	20	0	30	3	20	0	60	3	20	0	60
AD1	5	5	0	7	5	5	0	14	5	5	0	14
AD2	5	15	1	8	5	15	1	16	5	15	1	16
AD3	5	10	0	6	5	10	0	12	5	10	0	12
INT1	3	4	1	5	3	4	1	10	3	4	1	10
INT2	1	5	1	3	1	5	1	6	1	5	1	6
INT3	2	5	0	10	2	5	0	20	2	5	0	20
INT4	2	5	0	5	2	5	0	10	2	5	0	10
INT5	2	5	0	5	2	5	0	10	2	5	0	10
INT6	2	5	0	4	2	5	0	8	2	5	0	8
INT7	2	5	0	5	2	5	0	10	2	5	0	10
VER1	8	5	0	3	8	5	0	6	8	5	0	6
VER2	5	10	0	3	5	10	0	6	5	10	0	6
VER3	5	20	1	10	5	20	1	20	5	20	1	20
VER4	5	5	1	4	5	5	1	8	5	5	1	8
VAL1	5	3	1	5	5	3	1	10	5	3	1	10
VAL2	5	5	0	5	5	5	0	10	5	5	0	10
VAL3	3	5	1	5	3	5	1	10	3	5	1	10

Table E.1 Activity Resource Requirements and Durations for Deterministic Cases (Continued)

	Case D1: Small Scale and Low Resource Availability				Case D2: Large Scale and Low Resource Availability				Case D3: Large Scale and High Resource Availability			
	Resources Required			Constant Duration (Work Day)	Resources Required			Constant Duration (Work Day)	Resources Required			Constant Duration (Work Day)
Activity Code*	**SysEng**	**SME**	**PM**		**SysEng**	**SME**	**PM**		**SysEng**	**SME**	**PM**	
VAL4	3	10	0	3	3	10	0	6	3	10	0	6
VAL5	5	10	0	5	5	10	0	10	5	10	0	10
VAL6	3	15	0	2	3	15	0	4	3	15	0	4
VAL7	5	10	1	3	5	10	1	6	5	10	1	6
VAL8	5	5	1	3	5	5	1	6	5	5	1	6
MAINT1	2	3	1	2	2	3	1	4	2	3	1	4
MAINT2	2	5	1	3	2	5	1	6	2	5	1	6
MAINT3	1	3	1	5	1	3	1	10	1	3	1	10
MAINT4	0	5	0	3	0	5	0	6	0	5	0	6
MAINT5	0	5	0	5	0	5	0	10	0	5	0	10
MAINT6	0	10	0	60	0	10	0	120	0	10	0	120
MAINT7	0	10	0	60	0	10	0	120	0	10	0	120
MAINT8	1	3	1	60	1	3	1	120	1	3	1	120
OP1	2	5	0	10	2	5	0	20	2	5	0	20
OP2	2	15	0	5	2	15	0	10	2	15	0	10
OP3	2	15	0	60	2	15	0	120	2	15	0	120
OP4	2	15	0	60	2	15	0	120	2	15	0	120
OP5	2	10	1	60	2	10	1	120	2	10	1	120
DIS1	2	3	1	3	2	3	1	6	2	3	1	6
DIS2	2	3	1	2	2	3	1	4	2	3	1	4
DIS3	2	3	0	2	2	3	0	4	2	3	0	4
DIS4	0	5	0	5	0	5	0	10	0	5	0	10

Table E.1 Activity Resource Requirements and Durations for Deterministic Cases (Continued)

	Case D1: Small Scale and Low Resource Availability				Case D2: Large Scale and Low Resource Availability				Case D3: Large Scale and High Resource Availability			
	Resources Required			Constant Duration (Work Day)	Resources Required			Constant Duration (Work Day)	Resources Required			Constant Duration (Work Day)
Activity Code*	**SysEng**	**SME**	**PM**		**SysEng**	**SME**	**PM**		**SysEng**	**SME**	**PM**	
DIS5	0	5	0	5	0	5	0	10	0	5	0	10
DIS6	0	5	0	5	0	5	0	10	0	5	0	10
DIS7	1	3	0	5	1	3	0	10	1	3	0	10
SEP1	3	2	1	5	3	2	1	10	3	2	1	10
SEP2	3	2	1	20	3	2	1	40	3	2	1	40

*Shaded activities are high risk, others are low risk activities.

Table E.2 Activity Resource Requirements and Durations for Stochastic Cases

	Case S1: Small Scale and Low Resource Availability				Case S2: Large Scale and Low Resource Availability				Case S3: Large Scale and High Resource Availability			
	Small-scale & Low Resource Availability				Large-scale & Low Resource Availability				Large-scale & High Resource Availability			
Activity Code*	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**
SRD1	3	1	1	3, 3, 6	3	1	1	6, 6, 12	3	1	1	6, 6, 12
SRD2	3	1	0	3, 3, 6	3	1	0	6, 6, 12	3	1	0	6, 6, 12
SRD3	4	1	0	4, 4, 8	4	1	0	8, 8, 16	4	1	0	8, 8, 16
MA1	2	1	1	2, 2, 4	2	1	1	4, 4, 8	2	1	1	4, 4, 8
MA2	2	1	1	3, 3, 6	2	1	1	6, 6, 12	2	1	1	6, 6, 12
MA3	2	1	0	2, 2, 4	2	1	0	4, 4, 8	2	1	0	4, 4, 8
RA3	3	1	1	3, 3, 6	3	1	1	6, 6, 12	3	1	1	6, 6, 12
RA4	4	2	0	7, 7, 14	4	2	0	14, 14, 28	4	2	0	14, 14, 28
RA5	3	2	0	5, 5, 10	3	2	0	10, 10, 20	3	2	0	10, 10, 20
FA1	4	5	1	8, 8, 16	4	5	1	16, 16, 32	4	5	1	16, 16, 32
FA2	6	5	0	7, 7, 14	6	5	0	14, 14, 28	6	5	0	14, 14, 28
SS1	4	10	0	10, 10, 20	4	10	0	20, 20, 40	4	10	0	20, 20, 40
SS2	3	20	0	30, 30, 60	3	20	0	60, 60, 120	3	20	0	60, 60, 120

Table E.2 Activity Resource Requirements and Durations for Stochastic Cases (Continued)

	Case S1: Small Scale and Low Resource Availability				Case S2: Large Scale and Low Resource Availability				Case S3: Large Scale and High Resource Availability			
	Small-scale & Low Resource Availability				Large-scale & Low Resource Availability				Large-scale & High Resource Availability			
Activity Code*	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**
AD1	5	5	0	7, 7, 14	5	5	0	14, 14, 28	5	5	0	14, 14, 28
AD2	5	15	1	8, 8, 16	5	15	1	16, 16, 32	5	15	1	16, 16, 32
AD3	5	10	0	6, 6, 12	5	10	0	12, 12, 24	5	10	0	12, 12, 24
INT1	3	4	1	5, 5, 7.5	3	4	1	10, 10, 15	3	4	1	10, 10, 15
INT2	1	5	1	3, 3, 4.5	1	5	1	6, 6, 9	1	5	1	6, 6, 9
INT3	2	5	0	10, 10, 15	2	5	0	20, 20, 30	2	5	0	20, 20, 30
INT4	2	5	0	5, 5, 7.5	2	5	0	10, 10, 15	2	5	0	10, 10, 15
INT5	2	5	0	5, 5, 7.5	2	5	0	10, 10, 15	2	5	0	10, 10, 15
INT6	2	5	0	4, 4, 6	2	5	0	8, 8, 12	2	5	0	8, 8, 12
INT7	2	5	0	5, 5, 7.5	2	5	0	10, 10, 15	2	5	0	10, 10, 15
VER1	8	5	0	3, 3, 4.5	8	5	0	6, 6, 9	8	5	0	6, 6, 9
VER2	5	10	0	3, 3, 4.5	5	10	0	6, 6, 9	5	10	0	6, 6, 9
VER3	5	20	1	10, 10, 15	5	20	1	20, 20, 30	5	20	1	20, 20, 30
VER4	5	5	1	4, 4, 6	5	5	1	8, 8, 12	5	5	1	8, 8, 12
VAL1	5	3	1	5, 5, 7.5	5	3	1	10, 10, 15	5	3	1	10, 10, 15
VAL2	5	5	0	5, 5, 7.5	5	5	0	10, 10, 15	5	5	0	10, 10, 15

Table E.2 Activity Resource Requirements and Durations for Stochastic Cases (Continued)

	Case S1: Small Scale and Low Resource Availability				Case S2: Large Scale and Low Resource Availability				Case S3: Large Scale and High Resource Availability			
	Small-scale & Low Resource Availability				Large-scale & Low Resource Availability				Large-scale & High Resource Availability			
Activity Code*	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**
VAL3	3	5	1	5, 5, 7.5	3	5	1	10, 10, 15	3	5	1	10, 10, 15
VAL4	3	10	0	3, 3, 4.5	3	10	0	6, 6, 9	3	10	0	6, 6, 9
VAL5	5	10	0	5, 5, 7.5	5	10	0	10, 10, 15	5	10	0	10, 10, 15
VAL6	3	15	0	2, 2, 3	3	15	0	4, 4, 6	3	15	0	4, 4, 6
VAL7	5	10	1	3, 3, 4.5	5	10	1	6, 6, 9	5	10	1	6, 6, 9
VAL8	5	5	1	3, 3, 4.5	5	5	1	6, 6, 9	5	5	1	6, 6, 9
MAINT1	2	3	1	2, 2, 3	2	3	1	4, 4, 6	2	3	1	4, 4, 6
MAINT2	2	5	1	3, 3, 4.5	2	5	1	6, 6, 9	2	5	1	6, 6, 9
MAINT3	1	3	1	5, 5, 7.5	1	3	1	10, 10, 15	1	3	1	10, 10, 15
MAINT4	0	5	0	3, 3, 4.5	0	5	0	6, 6, 9	0	5	0	6, 6, 9
MAINT5	0	5	0	5, 5, 7.5	0	5	0	10, 10, 15	0	5	0	10, 10, 15
MAINT6	0	10	0	60, 60, 90	0	10	0	120, 120, 180	0	10	0	120, 120, 180
MAINT7	0	10	0	60, 60, 90	0	10	0	120, 120, 180	0	10	0	120, 120, 180
MAINT8	1	3	1	60, 60, 90	1	3	1	120, 120, 180	1	3	1	120, 120, 180
OP1	2	5	0	10, 10, 15	2	5	0	20, 20, 30	2	5	0	20, 20, 30

Table E.2 Activity Resource Requirements and Durations for Stochastic Cases (Continued)

	Case S1: Small Scale and Low Resource Availability				Case S2: Large Scale and Low Resource Availability				Case S3: Large Scale and High Resource Availability			
	Small-scale & Low Resource Availability				Large-scale & Low Resource Availability				Large-scale & High Resource Availability			
Activity Code*	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**	**SysEng**	**SME**	**PM**	**Triangular Duration** (Work Day)**
OP2	2	15	0	5, 5, 7.5	2	15	0	10, 10, 15	2	15	0	10, 10, 15
OP3	2	15	0	60, 60, 90	2	15	0	120, 120, 180	2	15	0	120, 120, 180
OP4	2	15	0	60, 60, 90	2	15	0	120, 120, 180	2	15	0	120, 120, 180
OP5	2	10	1	60, 60, 90	2	10	1	120, 120, 180	2	10	1	120, 120, 180
DIS1	2	3	1	3, 3, 4.5	2	3	1	6, 6, 9	2	3	1	6, 6, 9
DIS2	2	3	1	2, 2, 3	2	3	1	4, 4, 6	2	3	1	4, 4, 6
DIS3	2	3	0	2, 2, 3	2	3	0	4, 4, 6	2	3	0	4, 4, 6
DIS4	0	5	0	5, 5, 7.5	0	5	0	10, 10, 15	0	5	0	10, 10, 15
DIS5	0	5	0	5, 5, 7.5	0	5	0	10, 10, 15	0	5	0	10, 10, 15
DIS6	0	5	0	5, 5, 7.5	0	5	0	10, 10, 15	0	5	0	10, 10, 15
DIS7	1	3	0	5, 5, 7.5	1	3	0	10, 10, 15	1	3	0	10, 10, 15
SEP1	3	2	1	5, 5, 7.5	3	2	1	10, 10, 15	3	2	1	10, 10, 15
SEP2	3	2	1	20, 20, 30	3	2	1	40, 40, 60	3	2	1	40, 40, 60

*Shaded activities are high risk, others are low risk activities.

** Minimum, mode and maximum duration values are given as triangular distribution parameters.

APPENDIX F

REPLICATION NUMBER ESTIMATION RESULTS

Table F.1 Results For Replication Number Estimation Algorithm

	CASE S1				CASE S2				CASE S3			
Parameter Definition	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**
Replication Number (n)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Completion Time (Yi)	460.3	34.6	50.8	30.1	920.7	34.6	50.8	30.1	769.1	20.8	30.4	18.9
	476.4	34.0	52.5	29.1	952.8	34.0	52.5	29.1	786.7	20.8	31.5	18.0
	448.7	34.8	50.9	29.0	897.4	34.8	50.9	29.0	729.2	21.3	31.7	17.2
	445.1	34.7	51.5	28.6	890.2	34.7	51.5	28.6	754.7	20.6	29.8	18.3
	452.5	34.1	52.2	30.2	904.9	34.1	52.2	30.2	713.2	21.7	33.1	19.3
	447.6	35.4	52.3	28.1	895.3	35.4	52.3	28.1	760.3	20.9	30.2	18.1
	457.0	35.2	51.3	31.2	914.0	35.2	51.3	31.2	773.7	20.8	30.5	18.2
	448.0	35.3	50.9	29.6	896.1	35.3	50.9	29.6	752.2	21.1	30.5	17.4
	452.2	34.8	52.5	28.7	904.3	34.8	52.5	28.7	767.0	20.4	31.0	16.8
	465.5	35.6	52.0	29.6	931.0	35.6	52.0	29.6	776.7	21.4	31.6	17.4

Table F.1 Results For Replication Number Estimation Algorithm (Continued)

	CASE S1				CASE S2				CASE S3			
Parameter Definition	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**
Sample mean ($\bar{Y}$)	455.3	34.8	51.7	29.4	910.7	34.8	51.7	29.4	758.3	21.0	31.0	17.9
Sample variance (s^2)	94.8	0.3	0.5	0.8	379.5	0.3	0.5	0.8	501.2	0.2	1.0	0.6
Sample standard deviation (s)	9.7	0.5	0.7	0.9	19.5	0.5	0.7	0.9	22.4	0.4	1.0	0.8
Significance level (α)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Student-t distribution value ($t_{n-1, 1-\alpha/2}$)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
CI half length (h)	5.6	0.3	0.4	0.5	11.3	0.3	0.4	0.5	13.0	0.2	0.6	0.5
Relative precision (r)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Desired CI half length (h^*)	45.5	3.5	5.2	2.9	91.1	3.5	5.2	2.9	75.8	2.1	3.1	1.8
$h \leq h^*$ check	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Variance (σ^2)	9.5	0.0	0.0	0.1	37.9	0.0	0.0	0.1	50.1	0.0	0.1	0.1

Table F.1 Results For Replication Number Estimation Algorithm (Continued)

	CASE S1				CASE S2				CASE S3			
Parameter Definition	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**	**Project Duration**	**SysEng Utilization (%)**	**SME Utilization (%)**	**PM Utilization (%)**
Standard Deviation (σ)	3.1	0.2	0.2	0.3	6.2	0.2	0.2	0.3	7.1	0.1	0.3	0.2
CI Lower Limit	449.7	34.5	51.3	28.9	899.4	34.5	51.3	28.9	745.3	20.7	30.5	17.5
CI Upper Limit	461.0	35.2	52.1	29.9	922.0	35.2	52.1	29.9	771.3	21.2	31.6	18.4