January 2015

Industrial Adoption of Model-Based Systems Engineering: Challenges and Strategies

Apoorv Maheshwari
Purdue University

Graduate School Form 30
Updated 1/15/2015

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Apoorv Maheshwari

Entitled
Industrial Adoption of Model-Based Systems Engineering: Challenges and Strategies

For the degree of Master of Science in Aeronautics and Astronautics

Is approved by the final examining committee:

Dr. Daniel A. DeLaurentis
Chair

Dr. Jitesh Panchal

Dr. Nathan Hartman

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Approved by: Dr. Steven H. Collicott 12/7/2015

Head of the Departmental Graduate Program Date

INDUSTRIAL ADOPTION OF MODEL-BASED SYSTEMS ENGINEERING: CHALLENGES AND STRATEGIES

A Thesis

Submitted to the Faculty

of

Purdue University

by

Apoorv Maheshwari

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Aeronautics and Astronautics

December 2015

Purdue University

West Lafayette, Indiana

Dedicated to my parents.

ACKNOWLEDGMENTS

I would like to express the deepest appreciation to my advisor, Professor Daniel A. DeLaurentis, for his constant support to my work. His guidance and command on the topic helped me stay on track in the research work. I could not have imagined having a better advisor and mentor for my Master's thesis.

Besides my advisor, I would like to thank the rest of my thesis committee: Prof. Jitesh Panchal, Prof. Nathan Hartman, and Prof. Robert Kenley, for their insightful comments and encouragement, and also for the precise questions which incented me to widen my research from various perspectives.

My sincere thanks also goes to the INCOSE Biomedical Healthcare Challenge Team, who provided me with an opportunity to work on the interesting infusion pump design problem. Without their precious support and expertise, it would not have been possible to understand medical standards, let alone integrate the information with the model-based process representations.

Finally, I would like to thank my peers and friends within the SoS Lab and the Purdue University for all the stimulating discussions and good memories.

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ABSTRACT

Maheshwari, Apoorv M.S.A.A., Purdue University, December 2015. Industrial Adoption of Model-Based Systems Engineering: Challenges and Strategies. Major Professor: Daniel A. DeLaurentis.

As design teams are becoming more globally integrated, one of the biggest challenges is to efficiently communicate across the team. The increasing complexity and multi-disciplinary nature of the products are also making it difficult to keep track of all the information generated during the design process by these global team members. System engineers have identified Model-based Systems Engineering (MBSE) as a possible solution where emphasis is placed on the application of visual modeling methods and best practices to systems engineering (SE) activities right from the beginning of the conceptual design phases through to the end of the product lifecycle. Despite several advantages, there are multiple challenges restricting the adoption of MBSE by industry. We mainly consider the following two challenges: a) Industry perceives MBSE just as a diagramming tool and does not see too much value in MBSE; b) Industrial adopters are skeptical if the products developed using MBSE approach will be accepted by the regulatory bodies. To provide counter evidence to the former challenge, we developed a generic framework for translation from an MBSE tool (Systems Modeling Language, SysML) to an analysis tool (Agent-Based Modeling, ABM). The translation is demonstrated using a simplified air traffic management problem and provides an example of a potential quite significant value: the ability to use MBSE representations directly in an analysis setting. For the latter challenge, we are developing a reference model that uses SysML to represent a generic infusion pump and SE process for planning, developing, and obtaining regulatory approval of a medical device. This reference model demonstrates how regulatory requirements can be captured effectively through model-based representations. We will present

another case study at the end where we will apply the knowledge gained from both case studies to a UAV design problem.

PUBLICATIONS

1. Maheshwari, A., Kenley, C. R., & DeLaurentis, D. A. (2015, October). Creating Executable AgentBased Models Using SysML. In *INCOSE International Symposium* (Vol. 25, No. 1, pp. 1263-1277).

2. Maheshwari, A., Lott, M., Malins, R., Waterplas, C., Stein, J., Thukral, A., Kenley, C. R., & DeLaurentis, D. A. Application of systems engineering to regulatory compliance activities for medical devices. In *9th Great Lakes Regional Conference 2015.* International Council on Systems Engineering (INCOSE). *(Oral Presentation)*

1. Introduction

The origin of Systems Engineering (SE) as we know it today can be traced back to Ludwig von Bertalanffy [1] when he defined system as a 'whole' consisting of interacting 'parts'. Wymore, who is considered one of the founding fathers of SE, defined it as *"the intellectual, academic, and professional discipline, the primary concern of which is the responsibility to ensure that all the requirements for a bioware/hardware/software system are satisfied throughout the lifecycle of the system."* [2] Today, SE is defined in different forms by different organizations. Keating et al. [3] provides a good overview of different perspectives of SE. Three commonly used definitions of SE are as follows:

> SE is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. (INCOSE) [4]

> SE is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspects. (FAA) [5]

> SE is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. A system is a construct or collection of different elements that together produce results not obtainable by the elements alone. (NASA) [6]

The common recurring theme is that SE is an *iterative* approach that supports the complete *life-cycle* of the product and involves understanding *interaction* between sub-systems.

Over the years, SE gave us a number of important tools, including Quality Function Deployment (QFD) [7] [8], and Universal Systems Language (USL) [9], which revolutionized the engineering fields by designing systems with significantly increased reliability and productivity along with lowering the risk. Today, we stand at another such junction, where systems engineers have identified another approach, Model-Based Systems Engineering (MBSE), which can help us design better in the complex world.

1.1 MBSE: An Overview

A *model* is a representation of information that follows some specific guidelines and semantics. MBSE is defined by International Council on Systems Engineering (INCOSE), in their *SE Vision 2020* [10], as follows:

> MBSE is the formalized application of modeling to support system requirements, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life-cycle phases.

Thus, in simple words, MBSE is a more digital and visual approach to represent the SE processes. The main aim of the MBSE is to enhance the ability to capture, analyze, share and manage the system information. MBSE is often represented as a shift from document-centric to a model-centric approach to SE. In a traditional document-centric approach, information associated with different SE processes, such as specifications, interface requirements, system descriptions, analysis reports, trade-off studies and qualification processes, are contained in documents. In a model-centric approach, all of (or a part of) this information is captured in a model or a set of models. The author believes that this approach will result in significant improvements in the system design process due to the following advantages of MBSE over traditional SE:

- **Improved communication**: The model-based representations will improve the communication across the system stakeholders, within the project teams and across the spoken language barriers. It will help in reducing the loss of information due to the language differences.

- **Improved complexity management**: With the ability to view the system from different perspectives and to trace the impact of changes across the system design, it becomes easier to manage the complexity of the system.

- **Improved understanding**: Information can be captured in more standardized ways by creating logical models of the system. These models will help in providing a high of level of abstraction, enabling design reuse or sharing and thus, resulting in reduced cycle times and lower design costs.

- **Improved design of test cases**: With clearer representations of the system, it will be easier to identify the weaknesses in the system. For example, an improved understanding of information flow in a large complex system will help us in identifying the most critical sub-systems quickly.

- **Easier verification**: It will be easier to evaluate an unambiguous and precise system model for consistency, correctness, and completeness. This will also help in leveling of requirements to understand which requirement is more critical (or less critical) to the system design.

Before moving forward, it is important to understand that creating models to represent a system is not a new concept. In fact, this concept exists at the heart of scientific research where we constantly try to represent natural processes in forms of theories or equations. This evolution to model-based approach has happened in other domains in the past and will happen in the future as well (Figure 1.1). Thus, for SE, MBSE represents nothing but an evolution from low-fidelity representations in documents to higher-fidelity, richer representations of the SE methods.

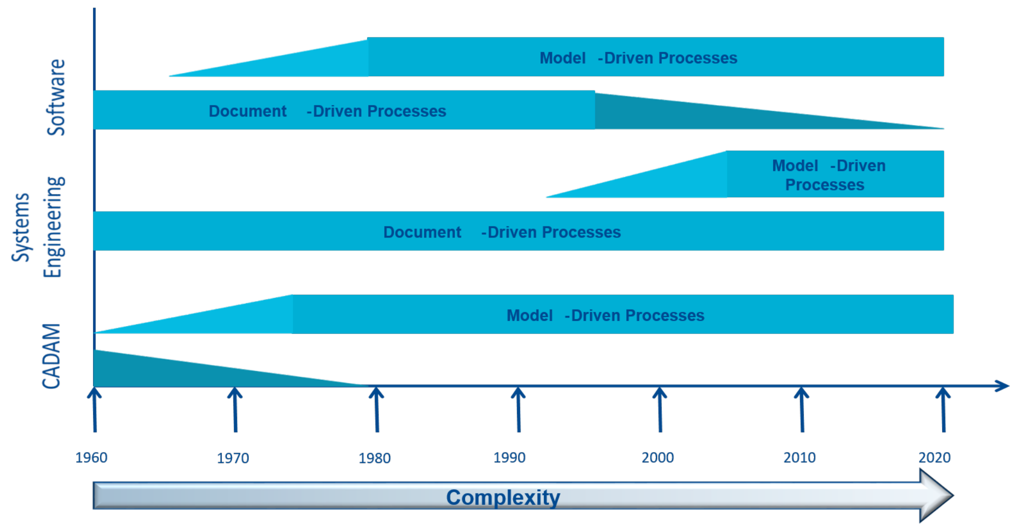


Figure 1.1. Transition to Model-based Approach in Different Domains [11]

1.2 MBSE: Status Quo

Since the inception of the theoretical and abstract discussion on MBSE from the late 1990s, when the transition towards model-driven engineering was happening for other engineering disciplines, there have been a lot of developments in MBSE. Today, MBSE is the focus when it comes to process efficiency improvement. We have more ready-for-use elements available and are moving towards the industrial adoption of MBSE. It was obvious from the very start that the transition to MBSE required a collaboration of different organizations. Thus, systems engineers identified standardization as a requirement in order to support this transition. A number of standards like Systems Modeling Language (SysML) [12], Application Protocal (AP) 233 [13], European Cooperation for Space Standardization-Engineering-Technical Memorandum-10-23 (ECSS-E-TM-10-23) [14], Orthogonal Variability Modeling [15], ISO 26550 [16], etc., have been developed since then. These standards are constantly developing while initial deployment has also started in parallel. We will discuss SysML in detail later.

Other than the standards, a lot of progress has been made in the development and application of MBSE in both academia and industry. We summarize major ongoing research in this area here. The author encourages interested readers to go through [17] [18] [19] to learn about more ongoing projects in MBSE.

Dave [20] provides a good summary of the ongoing MBSE work at the NASA Jet Propulsion Laboratory (JPL). JPL has been working on developing and applying MBSE to various systems engineering problems across different project types, activities and life-cycle phases. They have applied MBSE to approximately 20 different projects including Mars 2020, Orion, The Jupiter Europa Orbiter, Europa Clipper, The Soil Moisture Active Passive, etc. For example, they have used model-based system representations to help in design exploration across architectural variants for a fractionated spacecraft. They identified that MBSE was really useful in capturing a rich set of rules and constraints that characterize a produce-able architecture or a set of architectural variants.

While the JPL is working on the implementation of MBSE, Peak et al. [21] lists how academic institutions have been working on educating the community through graduate and professional courses on MBSE. For example, the MBSE Center [22], along with the industrial partners, have been using SysML as their specific implementation mechanism to teach MBSE concepts to the students and working professionals.

Buede [23] in his book *The Engineering Design of Systems* takes a model-based approach to key SE activities and introduces models and methods using a lot of examples from diverse domains. London [24] envisions a framework which can combine MBSE with best practices to generate and evaluate concepts more efficiently.

MBSE is gradually being adopted among big industrial companies as well. Boeing has been stressing on educating people about the concepts of MBSE for sometime now. They have been using the MBSE approach in an integrated data environment to support Integrated Product Architectures (IPA) incentive at Boeing. IPA is aimed at developing and deploying a common capability to enable Boeing engineers to integrate requirements, architectures, and analyses [25].

Rolls Royce, another major aerospace company, has also been exploring the MBSE for past few years with the focus on implementing different standards in their engineering processes. In their implementation, they have observed that with MBSE there has been a 20%-40% reduction in the number of requirements. Also, MBSE has been helpful in early verifiability and validation of the products [11].

The work on MBSE adoption is not only limited to the aerospace sector and has been picked up in the consumer packaged goods industry as well. Procter & Gamble have identified MBSE as a means to create persistent, traceable and reusable requirements over product and process life cycles. They are using Systemica^{TM} Systems Engineering Methodology for their work [26].

It is evident that the interest in MBSE is growing among the big industrial players. This is also observed in the various surveys done by INCOSE on assessing the adoption of the modeling in the systems engineering community since 2009 [27] [28] [29] [30]. It was observed in the latest survey results that the MBSE adoption has increased in the non-DoD/Defense industries such as Energy, Rail and Automotive when compared with previous survey results. Still almost 50% of the responses come from people representing companies from defense sector. The awareness about the MBSE pilots and adoption of MBSE has also increased over the years. Along with identifying the MBSE awareness, the survey also asked the responders to list major challenges in the MBSE adoption in the industry. We discuss these challenges in detail in the next section.

1.3 Challenges in adoption of MBSE by industry - Premiere to the Case Studies

With the help of the survey results [30], literature [31] [32] [33] and interactions with industry members [25] [26] [11], a number of roadblocks on the path of industrial adoption of MBSE have been identified. We categorize these challenges in the following broad categories:

1. **Tools and Methodologies Issues:** The industrial perception is that MBSE is just another diagramming tool which represents data in a more organized manner at a higher-level but provides no benefit in the later phases of product design like analysis, etc. For example, one of the survey respondents [30] said that, *"the fact that MBSE models cannot convert directly into simulation really stinks"*. Thus, to change the industrial perception, it is important to develop the ability to translate MBSE design representations to analysis models.

2. **Regulatory Issues:** The regulatory system is still mainly document-based and thus, industrial adopters are skeptical if the products developed using the MBSE approach will be acceptable by the regulatory bodies. To tackle this challenge, we need to show that the regulatory requirements can be captured at the same level (or even better) in the model-based representations.

3. **Legacy Issues:** Most companies have significant legacy product data existing in document-centric approach. But there is no simple (or inexpensive) translation process to convert that information to the model-centric format. This presents a big hurdle for the companies to apply MBSE to the existing products.

4. **Cost/Return on Investment Issues:** It is difficult to measure the impact of MBSE on the product design. Thus, it is often asked if the investment in MBSE is worth the cost incurred in the implementation. Development cost-per-project can be one such metric to measure the impact of MBSE. An independent study done by Embedded Market Forecasters, based on 667 respondents, showed that model-based approaches cost 55% less and slightly improve on-time delivery when compared with traditional SE approaches [34].

5. **Lack of Skilled Practitioners:** Another major inhibiting factor is the lack of MBSE-skilled practitioners in the industry who can not only execute the

model-based projects but also educate management or fellow practitioners in other parts of the adoption curve than early adopters. This challenge can be tackled by increasing the number of MBSE-educating centers (like GaTech) and also, by demonstrating the value of MBSE through more case studies.

Among the aforementioned challenges, we will focus on the following two research questions in our work:

- *What are the features of an effective framework for translating model-based conceptual representations to analysis models?*
- *What are the specific products in a typical model based representation that, when properly formed, could be used to satisfy the regulatory requirements? And do these model based representations provide any benefit over the document-based approach?*

In Chapter 2, we will propose and demonstrate a translation framework to translate a model-based representation to an agent-based simulation model. We will also discuss some of the challenges associated with the proposed framework. In Chapter 3, we will apply a model-based design methodology to a safety-critical biomedical device and represent regulatory requirements using model-based approach. In Chapter 4, we will revisit the framework suggested in the Chapter 2 and modify it to handle some of the identified challenges. We will demonstrate the modified framework through a UAV design case study while adapting and implementing the process explained in the Chapter 3. Finally, we conclude with the insights gained through the work and suggest some future research directions in the Chapter 5.

2. Not just a Diagramming Tool!

Simulation plays an important role in the analysis of alternatives during the early phases of systems engineering activities. In this chapter, we try to identify the features of the framework that can translate model-based representations to analysis models effectively. We develop and demonstrate a generic framework to translate a SysML conceptual model to an executable agent-based simulation model using a simplified air traffic management problem. Along with the potential advantages, we also identify major challenges and possible mismatches in accomplishing a suitable translation for real-world complex systems.

2.1 Science of Integration

Product Lifecycle Management (PLM) is defined as the process of managing the entire lifecycle of a product from requirements identification, through design and manufacture, to service and disposal of manufactured products. In the current state, PLM and MBSE can be considered as two different approaches to product development which have evolved from different requirements. PLM is the evolution of the Product Data Management (PDM) approach, which was suggested to manage and track the creation, change and archive of all product-related information. The PDM concept was extended in PLM to manage all information around a manufactured product throughout its lifecycle. On the other hand, MBSE is being developed to advance the practice of SE with an objective to produce a more complete, consistent and feasible system specification upon which the product can be built. Due to these different requirements, PLM has evolved into a system that supports the management of document variants, change processes and product configuration but lacks in the transportation of semantic, computer-interpretable information throughout the

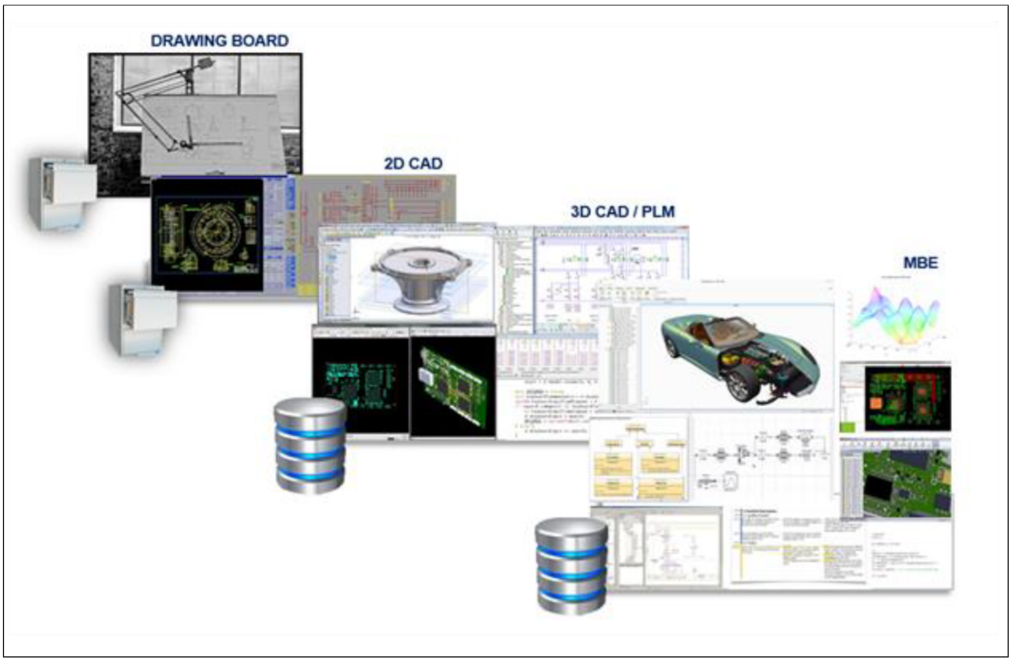


Figure 2.1. Evolution of product development from the Drawing Board to Model-Based Engineering [35]

lifecycle whereas MBSE can model the semantic information of a product but lacks in managing it throughout the lifecycle. Thus, to realize the complete potential of both PLM and MBSE approaches, the new generation PLM must itself be *Model-Based* by incorporating more structured information with meaning and follow a stronger model-based approach than it does today. This integration of PLM and MBSE is commonly referred to as Model-Based Engineering as shown in the Figure 2.1.

Boeing identifies the current lack of integration of MBSE representations with the phases and tools downstream to the design representation as one of the major roadblocks in the industrial adoption of MBSE [25]. Figure 2.2, usually referred to as the PLM Circle, shows the different phases of the product lifecycle. The current MBSE literature is more focused and developed on the first two stages of this PLM circle, namely, *Requirements* representation and *Design* representation. The MBSE representations are also quite developed to represent the process going from the requirements phase to the design phase. The main challenge exists in going from the

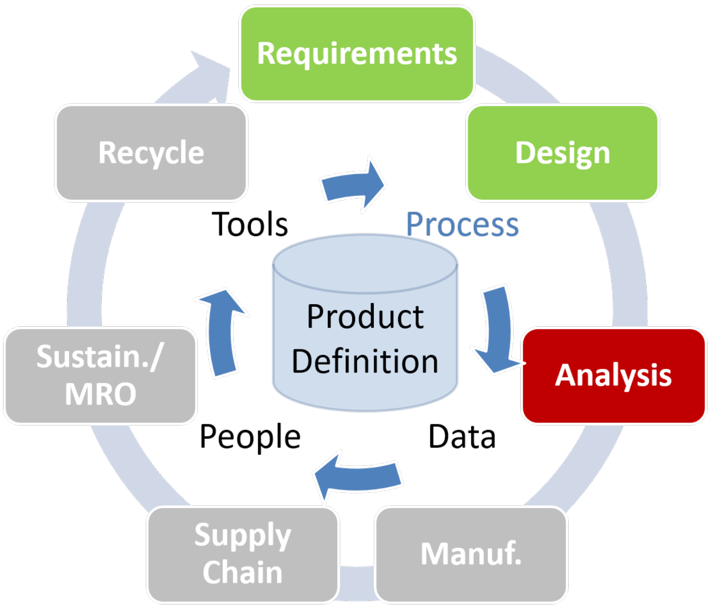


Figure 2.2. The PLM Circle [36]

design phase to the following analysis phase. Without this link, it is very difficult to realize the actual potential of the well-organized MBSE representations. Figure 2.3 is another representation of the model-based design process. It stresses more on how the link between the analysis and standard design library-based representations will lead into the further stages of the product lifecycle management. In this chapter, we will focus on the area (and the arrow) marked in green (Fig. 2.3). Connecting the model-based design representations with the analysis tools is the first step towards the integration of MBSE with PLM.

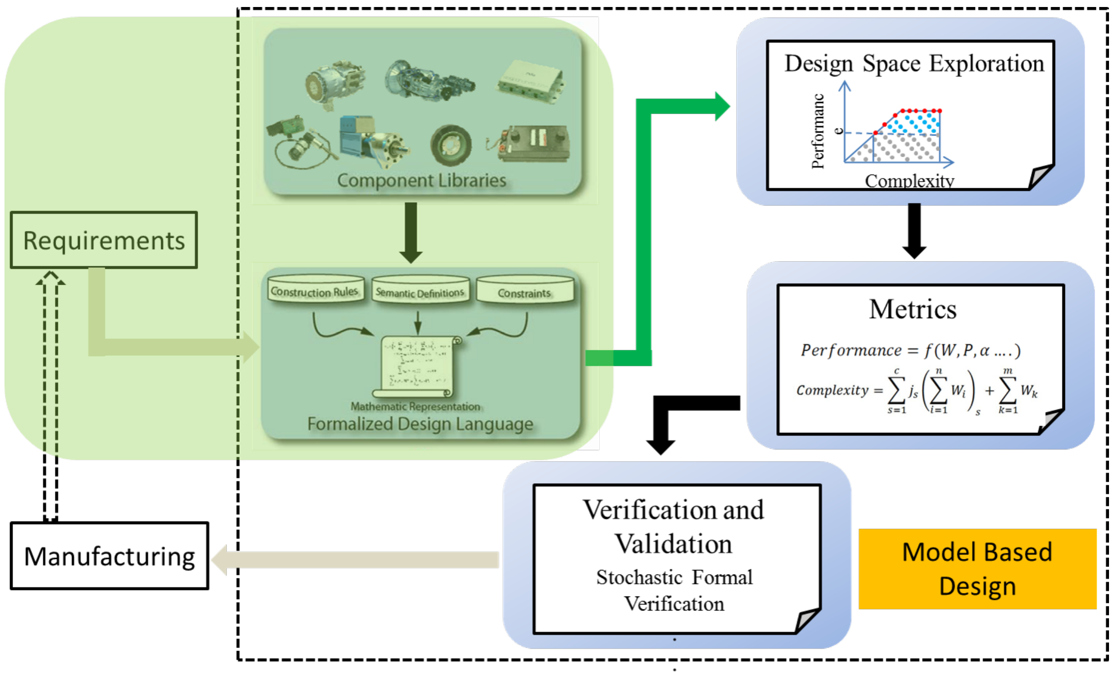


Figure 2.3. Model Based Design

2.2 Translation Framework

Kenley et al. [37] reviewed agent-based simulation models for systems of systems and MBSE methods that are applicable to specifying a system of systems. Their agent-based models are built from executable MATLAB code that simulates an allocated system-of-systems architecture where each function is modeled as an agent operating in a network of multiple, independent interacting agents [38]. The models simulate their functionality and operational effects, such as computational and communications latency, that are a consequence of the physical properties of the allocated architecture. They used the intra-agent dynamics model of an agent 2.4 to develop a UML (and by extension SysML) activity diagram. The dynamics model defines functions that:

- update the knowledge, beliefs, and information of the agent using inputs from its environment;
- decide on actions that achieve its objectives and desires; and
- take action that produces outputs that affect its environment.

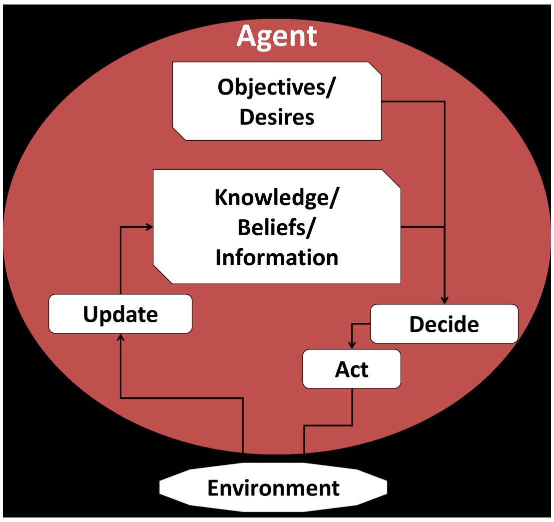


Figure 2.4. Behavioral model of an agent (adapted from [39])

In this chapter, we demonstrate a process for translating a system-of-systems architecture specified in SysML to an executable agent-based model. Similar work has been done by [40] where they used SysML as a diagramming tool to represent agent-based models. The main aim of their work was to investigate the effectiveness of SysML in establishing a conceptual model for agent-based modeling. However, in our research, we use SysML models to define the system and we seek to add a use by extracting information useful for agent-based simulation. Designing for Adaptability and evolutioN in System of systems Engineering (DANSE) project which has been working on developing methodology to support evolutionary, adaptive, and iterative lifecycles for systems of systems is another example where SysML models are combined with tabular data to automatically generate architecture variants for system analysis.

The generic schematic for translation from SysML to a simulation model is shown in Figure 2.5. This schematic is similar to the work of McGinnis et al. [41], who apply a model-driven architecture approach to develop a discrete event simulation from a SysML model of semiconductor manufacturing. Two distinct domain-specific toolboxes are mentioned in Figure 2.5. The domain-specific toolbox on the left is dedicated to the description of conceptual models using SysML whereas the toolbox on the right is the tool that is used to create an agent-based simulation model. The middle part consisting of three ovals represents the steps to achieve this translation. The first step is to understand the conceptual similarities and differences in how SysML and agent-based models represent the key aspects of a system of systems, namely, system definition and system inter-dependencies. These aspects are discussed in Section 2.3. The next step is to understand mappings between the domain-specific toolboxes. To achieve this, we need to understand the interface between SysML specifications and the agent-based model. This interface is discussed in Section 2.4. Once the mapping between the domain-specific toolboxes is completely understood, the final step is to translate the conceptual model prepared using SysML to an executable agent-based model. This translation is explained using a simple example in Section 2.5. The demonstration problem centers on a system of systems for air traffic control that was represented in SysML and interfaced with an executable agent-based modeling code written in MATLAB that simulates the operational activities of the system of systems.

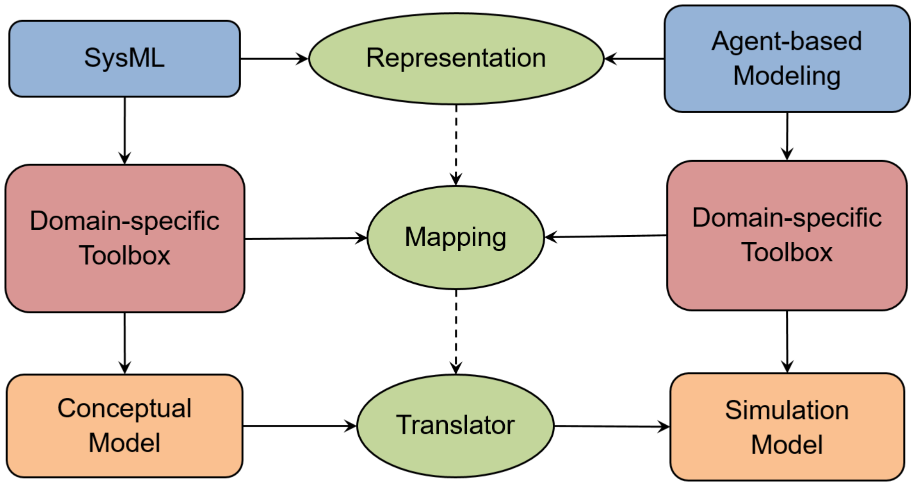


Figure 2.5. Translation Framework for SysML to ABM

2.3 Aspects of SysML and Agent-based Representations

The Systems Modeling Language, commonly known as SysML, has been specifically developed for model-based systems engineering to formalize the change from document-based to a model-based form of organization of information. It is a general-purpose modeling language, supporting the specification, analysis, design, verification, and validation of systems.

Agent-based modeling is a modeling approach to simulate the simultaneous actions and interactions of multiple autonomous agents (individual or collective) and understand the effects of the combined actions and interactions on the system as a whole. By allowing a designer to visualize these effects, it becomes possible to understand the root causes of the effects and to improve the modeled system. With its bottom-up approach, agent-based modeling is flexible in adapting to new architectures by integrating or removing any physical component or functional capability from the system. These advantages make agent-based modeling a very useful modeling and simulation approach for systems of systems.

An agent-based model represents a system of systems using four basic elements:

1. **Agents/Objects:** The set of all simulated or passive heterogeneous entities that interact with the environment based on their interaction rules.

2. **Space:** The environment where agents and objects are located and signals propagate. The space can be both discrete and continuous.

3. **Time:** The system evolves over time. The system can evolve over both discrete and continuous time intervals. For most of engineering problems, time can be considered as one of the dimensions of the environment.

4. **Dynamics:** The interaction rules and behaviors of all the agents that determine their actions and changes in state.

McGinnis et al. [41] identify a growing need for translating a conceptual model (such as the one created in SysML) directly to a simulation program to formalize and automate a substantial portion of the implementation side of the simulation process. Schönherr et al. [42] tried to build SysML models after identifying and structuring the significant properties of discrete processes mainly for production systems. IBM's Haifa Research Lab uses a generic SysML-based methodology for improving the architectural design phase [43]. In this chapter, we identify the key elements of SysML, viz. viewpoints and network representations, which can be used to map SysML models to agent-based simulations. We also demonstrate the translation with an agent-based simulation from the air traffic management domain.

2.3.1 Viewpoints

SysML defines four set of viewpoints - structural, behavioral, requirements, and parametric. The structural viewpoint defines the elements (including the composition of systems, their properties, and organizational grouping) of the systems using the block definition diagram and the internal block diagram. The behavioral viewpoint explains the interaction and architecture of the system using activity, sequence, state machine, and use case diagrams. The requirements viewpoint functions as a require-

Table 2.1. Similarities between SysML and agent-based modeling

Viewpoints	**SysML**	**Agent-Based Modeling**
Structural	Element definition	Agent definition
Behavioral	Interaction and architecture of the system	Information flow between the agents
Requirements	Requirement management tool	Verification of agent-based model (indirect)
Parametric	Logical/mathematical constraints on the design	Parameters of intra-agent dynamics

ments management tool keeping all the requirements in one place, making it easier for a systems engineer to create, relate, trace, and analyze them. Finally, the parametric viewpoint explains the constraints on the design via logical and mathematical expressions.

For agent-based modeling, structural viewpoints serve as the basis of defining various agents being simulated. Properties of the elements defined in the SysML can be directly mapped as the agent properties in the simulation. The behavioral viewpoint maps to the interaction and information flow between and within the agents in the simulation. The requirements viewpoint can be indirectly associated with verifying and analyzing the outcomes of the simulation but cannot be directly mapped with the functioning of the agent-based model. Finally, the parametric viewpoint defines the parameters of intra-agent dynamics for every agent. These similarities are summarized in the Table 2.1.

Though the congruence between the SysML viewpoints and the corresponding agent-based viewpoints seems significant, mismatches are possible. One of the major advantages of agent-based modeling is its ability to easily create multiple instances of an agent and analyze their interaction. In SysML, although it is possible to create multiple instances of the same element, it becomes relatively difficult to manage the links and the interactions once the number of instances becomes high. Another possible mismatch may occur in the ability to trigger a particular event at a specific point in time. Since SysML viewpoints are static representations of different components of the system, it is difficult to trigger events dynamically in the simulation using SysML. State machines can be used to represent various event triggers in SysML but proper extraction of the information relevant for agent-based simulation has not been achieved yet.

2.3.2 SysML Networks

Another important feature of SysML is its representation of networks. SysML can represent two types of architectures (or networks) used in cyber-physical design: logical and physical [44]. Logical network architectures describe the exchange of information between systems by explaining what information is transferred between systems. The physical network architecture shows the connectivity of systems by explaining the physical paths over which the information is transferred. For example, a logical network connection may specify that - when the driver presses the brake pedal, the information to slow down the car flows in the system. The related physical network would show the hydraulic configuration which is transferring the information from the brake pedal to the road-wheel brakes. The combination of these two types of links articulates that the brake pedal transfers information to slow down the car to the brakes using hydraulics, where both the action and the medium may have differing properties. Keeping these two networks separate allows for changes to either network without necessarily altering the other. For example, both the foot brake and the parking brake have the same logical networks but different physical networks. The driver just knows that the car will slow down by pressing the brake pedal and thus, the driver only knows about the logical network. The driver does not need to know about the underlying physical network to interact with the system. Similarly, in an agent-based model, this distinction between the path of interaction and the medium of interaction can help in modeling the system in a more generic way. Moreover, it also presents an opportunity to analyze the effects of different logical and physical concepts separately.

In an agent-based model, an agent changes its state based on its internal logical relations and external stimuli. Thus, an agent-based model represents these networks by specifying the interaction rules and the information flow for the agents. The distinction between a logical and a physical network surely helps in understanding the problem in a greater depth but this distinction might not be readily visible in an agent-based model at times. In those situations, direct translation of SysML networks to agent-based dynamics can be problematic (or, at worse, completely incorrect).

2.4 Interfacing SysML Specifications to Agent-based Simulation

After understanding the system-of-systems representation from the perspectives of both SysML and agent-based modeling, the next step is to understand the mapping between the domain-specific toolboxes of each field. In this work, we create the SysML model for the simulation in a SysML-enabled visual toolbox MagicDraw. MagicDraw is a visual SysML modeling tool that supports the latest OMG SysML Specification 1.3 version. The simulation for the generated SysML models is then translated to and executed in MATLAB by the Discrete Agent Framework (DAF) [45], developed at the System-of-Systems Laboratory, Purdue University. DAF is a MATLAB-based framework that provides the underlying infrastructure for agent-based simulation that moves messages around and maintains the simulation environment (locations, time, etc.). The link between MagicDraw and DAF is facilitated by ParaMagic, a plugin for MagicDraw. The complete translation mechanism is summarized in the Figure 2.6.

Based on the system definition, the elements of the system are defined in MagicDraw using the block definition and internal block diagrams. While designing the elements, requirements and constraints are created for each element using the requirements and the parametric viewpoint. Next, based on the architecture, logical

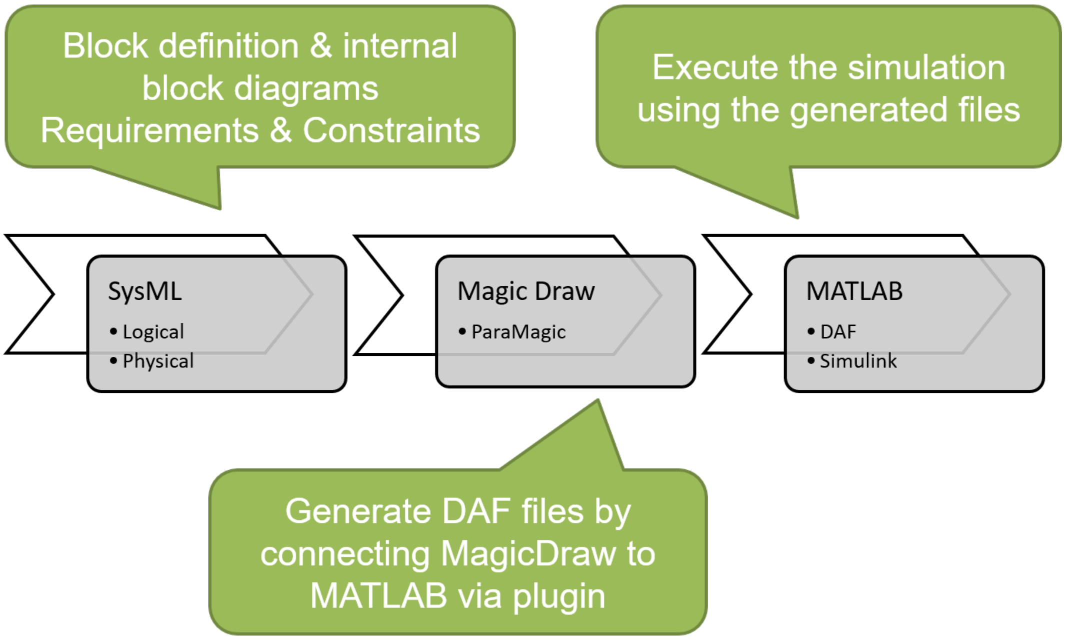


Figure 2.6. Translation Mechanism

and physical SysML networks of the system are created in MagicDraw. Once the SysML model is completed, the MagicDraw output artifacts are connected to the MATLAB using ParaMagic. ParaMagic helps in executing constraints relationships in SysML parametric diagrams through MATLAB and other math toolboxes. This MATLAB link is used to generate the files required for setting up the DAF simulation with the information from the SysML model. Once the required files are generated, an agent-based simulation is executed using DAF.

There are major challenges in achieving this translation from SysML model to an executable agent-based model. The primary challenge is to develop a mapping between the two domain-specific toolboxes (i.e. MagicDraw for SysML and DAF for agent-based modeling). The generic mapping has been developed in the previous section, but it is still difficult to find a publically available formal specification for all the toolboxes.

Another challenge, of course, is the development of the model translator, which uses the aforementioned mapping to translate a conceptual SysML model to an executable simulation model. This translator needs to be developed for each set of domain-specific toolboxes being used.

2.5 The NextGen Air Traffic Control System of Systems

The National Airspace System (NAS) consists of all the components (such as airspace, facilities, equipment, and procedures) that enable the United States air transportation system. The Next Generation Air Transportation System (NextGen) initiative was created to transform the NAS to a safer, more reliable, more efficient and an environment-friendly system. It proposes, for example, a transformation in the surveillance function from a ground-based system to a satellite-based system. It plans to use precision navigation technology to shorten routes, save time and fuel, reduce traffic delays, increase capacity, and permit controllers to monitor and manage aircraft with greater safety margins.

Modeling and simulating any new concept is crucial, especially when both safety and cost-effectiveness are at play. NextGen is a prime example. Simulations of new concepts can not only save time compared to physical experiments, but can also create a coherent synthetic environment that allows for integration of the simulated systems in the early analysis phase. Here, we demonstrate a simulation of one of the most important NextGen elements, the Automatic Dependent Surveillance-Broadcast (ADS-B) technology. In Next Gen, ADS-B will provide air traffic controllers and pilots more accurate information, based on GPS and inter-aircraft communication, to keep aircraft safely separated in both airborne and ground settings. In the demonstration, we simulate a simplified air traffic management problem.

Air traffic management encompasses all systems that assist aircraft to depart from an airport, transit airspace, and land at the destination airport. [46] states that air traffic management consists of mainly three distinct activities:

1. **Air Traffic Control (ATC):** This process is responsible for maintaining the appropriate separation between the aircraft to ensure the safety of the flying aircraft. Currently, the air separation is maintained by communication between pilots and air traffic control centers. In NextGen, ADS-B is meant to improve this communication link by broadcasting the aircraft information directly to its nearby aircraft.

2. **Air Traffic Flow Management:** This process deals with the planning of flight paths and timings. This is done before the flight takes place.

3. **Aeronautical Information Services:** These services are responsible for the compilation and distribution of all aeronautical information (including safety, navigation, technical, administrative, or legal) necessary to airspace users.

In our demonstration, we prepare a simplified model of the ATC section of the air traffic management, to illustrate the translation from SysML to DAF for a system of systems. Based upon the Mark Maiers description of the unique traits of systems of systems, there are two primary traits that are necessary for a group of systems to be considered as a system of systems: operational independence and managerial independence [47]. Operational independence implies that each system is capable of performing a set of functions without any interactions from the other systems. Managerial independence implies that the systems manage themselves to a purpose separate from the ultimate purpose of the system of systems. For the Air Traffic Control system, the aircraft can be considered as an operationally independent system performing the task of travelling from an origin to a destination along with satisfying the overarching goal of fulfilling the demand of the air transportation network.

Our model consists of a group of aircraft, equipped with ADS-B as the only communication technology, approaching each other. ADS-B consists of two sub-systems: ADS-B In (component responsible for receiving the other aircraft information) and ADS-B Out (component responsible for transmitting the aircraft information). All the aircraft are required to maintain a fixed minimum separation from other aircraft to reduce the risk of aircraft collision, as well as prevent accidents due to wake turbulence. Air traffic control enforces minimum separation rules to achieve this (FAA order 7110.65). A defined loss of separation between airborne aircraft occurs whenever the specified separation minima in the controlled airspace are breached. In such cases, a system known as the Airborne Collision Avoidance System (ACAS) comes into action to avoid collision. In simpler terms, if the separation bubbles of two aircraft intersect at any time, both aircraft change direction as per the collision avoidance algorithm. The ADS-B can broadcast and receive the aircraft information within a fixed distance. Thus, the aircraft can see other aircraft only if it is within the range of its ADS-B In. Fault is also introduced in the simulation by shutting off the ADS-B In system of an aircraft by a pre-defined trigger. With a faulty ADS-B In, the aircraft fails to see other aircraft in its ADS-B In range.

The Aircraft agent can divided in mainly two parts:

1. *Subsystem* containing all the communicating sensors and the auto-pilot system responsible for driving the agent. To simplify the implementation, both the

communicating sensors and the auto-pilot system are considered under this single section.

2. *ACAS*, the collision avoidance system which makes decisions regarding the agent's flight path based on the information about other agents and the separation rules.

The working of Aircraft agent is defined in the Figure 2.7, which is consistent with Figure 2.4 and is patterned after the activity diagram of a generic agent from [37]. The ADS-B In receives the State Vector (position and heading direction) of the aircraft that are within the range of the ADS-B In. Based on this input, the subsystem updates the state vector database. This information is then transferred to the ACAS, which decides upon the flight path based upon this information and the objective to maintain a minimum distance from other aircraft. This updated path is now sent to the subsystem as a command for the auto-pilot module. Simultaneously, the communication module broadcasts the updated state vector of the aircraft using ADS-B Out. In our demonstration, the logical network (Figure 2.8) consists of relevant information going to and from aircraft agents. The physical network (Figure 2.9) consists of the specific ADS-B In and ADS-B Out communication implementations.

For this example, after defining the block diagram of the aircraft agent, we create a parametric diagram for the agents which utilizes the ParaMagic plugin and MATLAB script to convert the parameters of each aircraft into agent files required for the DAF simulation. Since all the agents in our simulation are of the same type, we convert their specifications (i.e., initial positions and initial velocities) directly from one parametric diagram. A screen-shot of the parametric diagram is shown in Figure 2.10.

The constraint block shown above uses the MATLAB script `matlab_aircraft` to generate the required DAF agent files. The parameters are input into this MATLAB script and it gives the output flag a value (1, if file generation is successful and 0 otherwise). The DAF agent file is generated in the same folder as the MATLAB script.

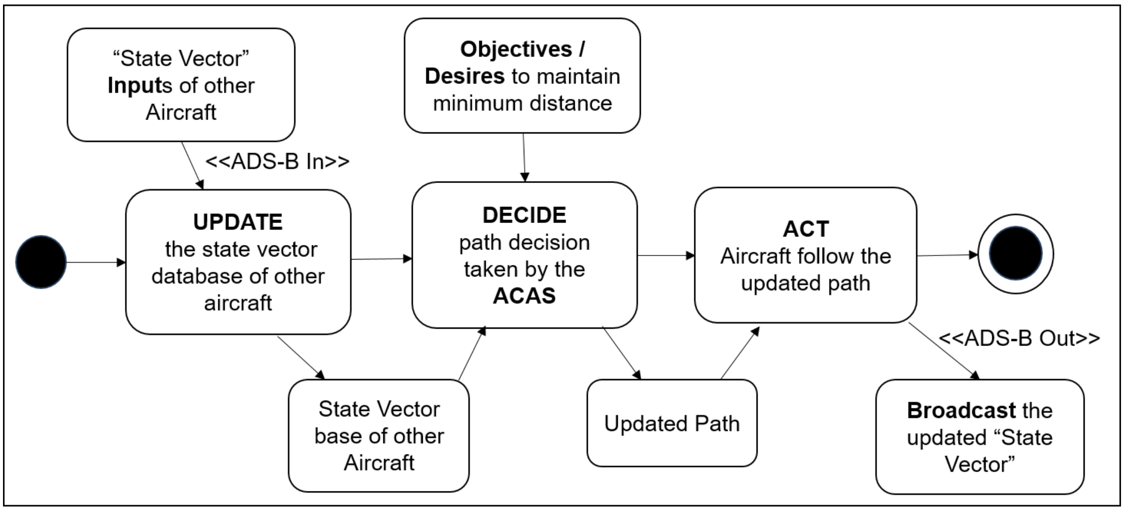


Figure 2.7. Activity Diagram for Aircraft agent

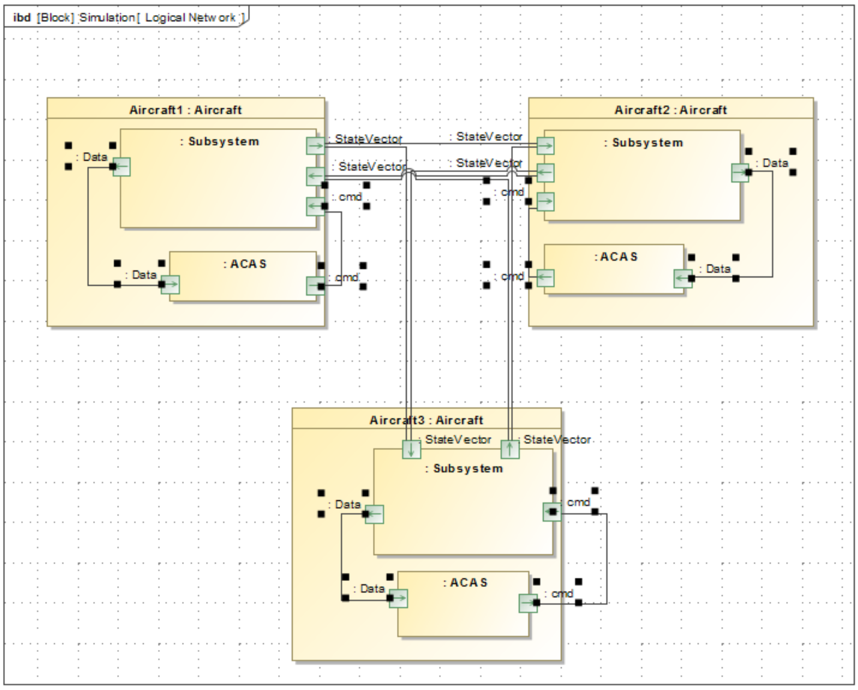


Figure 2.8. Logical Network

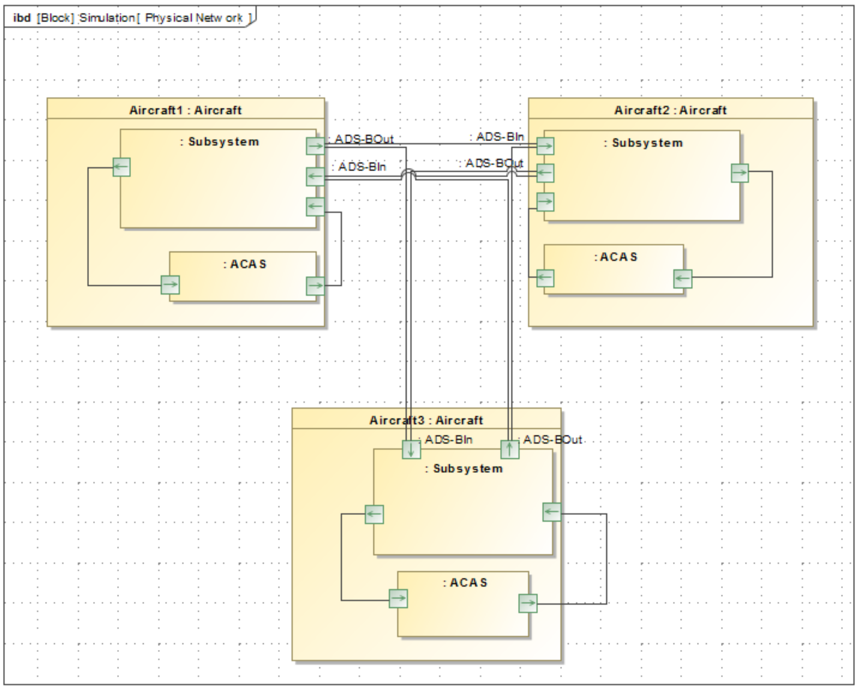


Figure 2.9. Physical Network

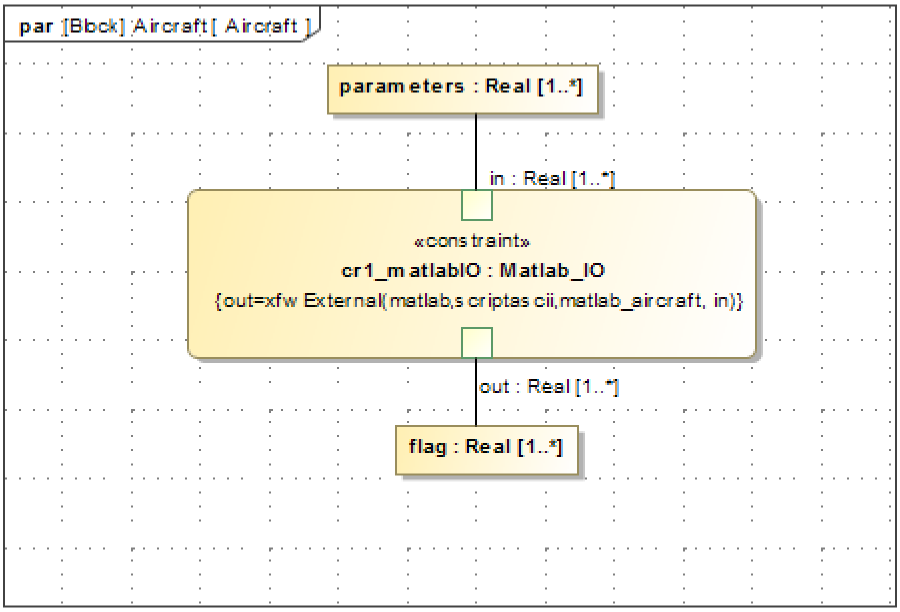


Figure 2.10. Parametric diagram for DAF agent file generation

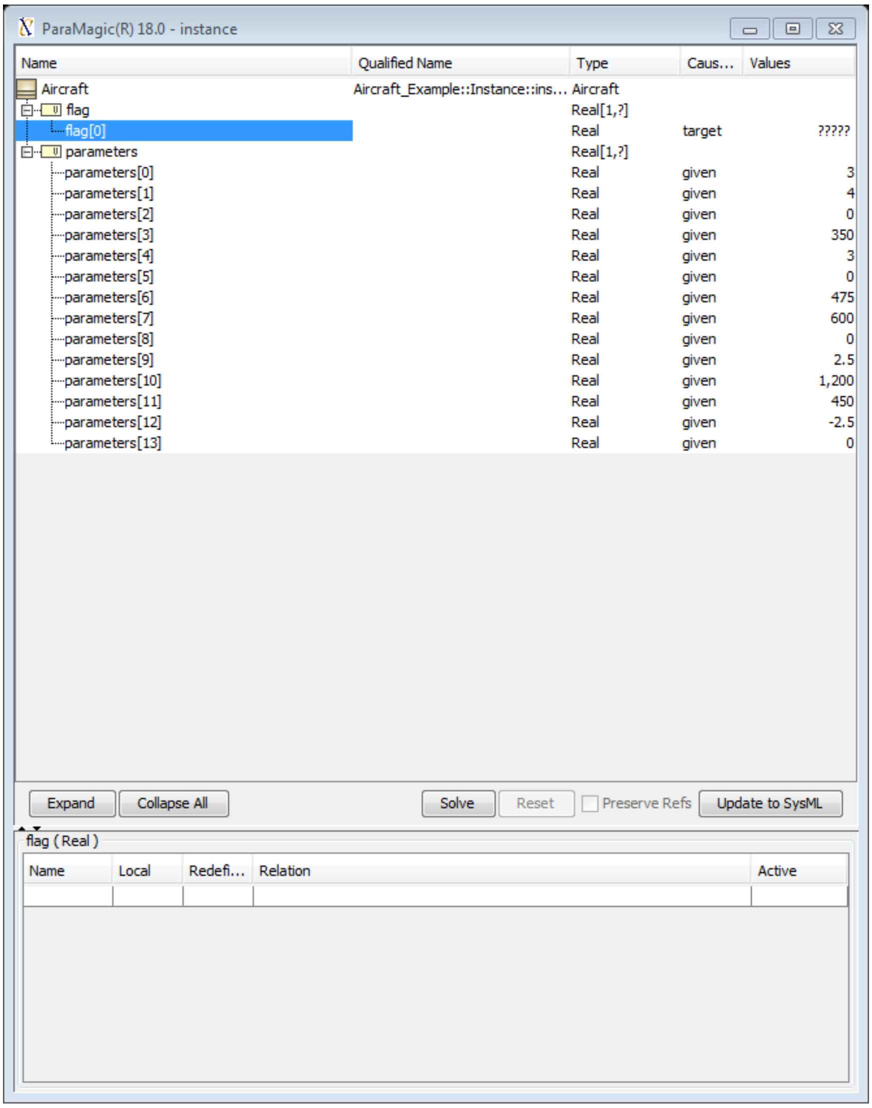


Figure 2.11. ParaMagic instance browser for agent file generation

Figure 2.11 shows Instance browser for one such run. Note that all the parameter values are given, and the flag value is the target value of the run. The first two entries of parameters represent the number of aircraft and number of specifications for each aircraft respectively. The rest of the values represent initial position (x-component), initial position (y-component), initial velocity (x-component) and initial velocity (y-component) for each aircraft in that order.

2.6 Results of the Simulation

After creating the SysML networks and establishing the connection between SysML and DAF, the agent-based simulation was executed with a group of aircraft agents working based on the established rules and objectives. The simulation snapshots are tabulated in Figure 2.12.

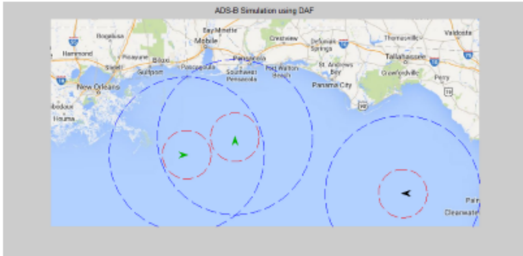
The range of ADS-B In is denoted by the blue circle in the simulation. The red circle denotes the critical separation zone for each aircraft. As soon as another aircraft comes in the ADS-B In range, the aircraft receives the data (starts seeing the aircraft) and turns green. When the separation bubbles of two aircraft intersect, both aircraft change their path based on the collision avoidance algorithm to maintain the minimum separation. Right now, a very simplified collision avoidance algorithm is implemented where aircraft move in the direction perpendicular to the vector formed between the two aircraft. The faulty aircraft is denoted by turning its marker red. We can see in the simulation that the faulty aircraft does not change path because it cannot see the other aircraft in its ADS-B In range.

Thus, we can see that a proper translation from SysML to an executable agent-based simulation model can be achieved. But there are two major issues that remain to be settled:

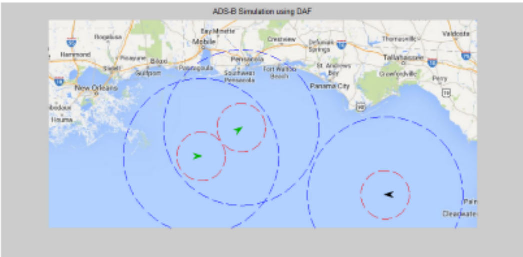
1. **Scalability:** The example problem is a very simplified version of a real-world situation. We observed in the example with three same type of agents with four specification parameters for each, the number of parameters needed for each simulation is 14. A more comprehensive and detailed version could be very large and complex, with a number of different agents involved and many instances of each. The construction and organization of such a large simulation is a major challenge of its own, but so may be the ability of this SysML-ABM mapping approach.

2. **Coarse-Graining:** To achieve an efficient mapping, we should be able to first identify and then extract all the *relevant* information from the SysML model to

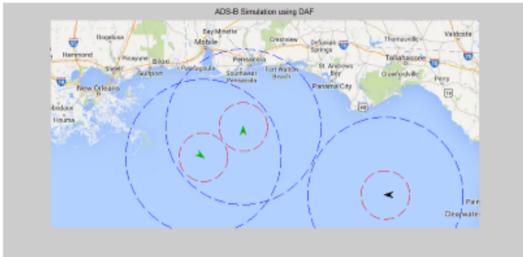
a. Three aircraft approaching each other



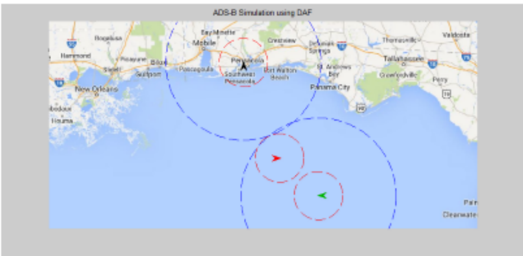
b. Aircraft 1 & 2 receiving information



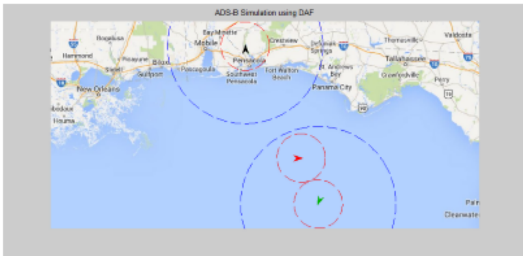
c. Aircraft 2 changes direction to maintain separation



d. Aircraft 1 changes direction to maintain separation



e. Aircraft 1 cannot *see* Aircraft 3 because of fault in its ADS-B In



f. Only Aircraft 3 changes direction to maintain separation

Figure 2.12. DAF Simulation Results

create an executable agent-based simulation model. The identification, extraction and management of this information is a difficult task and depends heavily on the knowledge about the internal functioning of both domain-specific toolboxes (of SysML and the agent-based simulation model). For example, in the demonstration problem, we assume the network of aircraft agents to be fully connected and thus, we were able to minimize the relevant information to the initial state characteristics of each aircraft. In a real world complex system, our network might not be fully connected and we will have to transfer this information from SysML to agent-based modeling tool. This information can be really difficult to extract and manage.

2.7 Lessons Learned

In this chapter, we showed how we can use a conceptual system representation in SysML to get an executable agent-based simulation. We also identified major challenges in achieving this translation for a real-world system. We explained a generic translation framework with the help of simple air traffic management problem. The framework helped us automate the simulation process, to some extent, directly from the SysML model. We were able to generate agent files required for the ADS-B simulation directly from the SysML element definition. The case study proves that this translation can be achieved, but we still have major challenges including scalability of the efficiency in the mapping process. While working on the translation, we also realized that automating the analysis process for a model-based system definition of complex real-world systems requires development of formal specifications for the domain-specific toolboxes involved.

3. Tackling the Regulatory Issues

In this chapter, we discuss the model-based approach to the engineering design of systems given by Buede [23]. We demonstrate the abstract nature of the approach by applying it to a Healthcare design problem and see if we can capture the regulatory requirements in the model-based representations.

3.1 Introduction to the Engineering Design of Systems

In his book, *The Engineering Design of Systems* [23], Buede describes the engineering of a system as *"the engineering discipline that develops, matches, and trades off requirements, functions, and alternate system resources to achieve a cost-effective, life-cycle-balanced product based upon the needs of the stakeholders".* He explains it further using the famous *"Vee"* diagram (Fig. 3.1) where the design process starts at the top left of the diagram with the definition of the operational needs of the stakeholders. These needs are then further decomposed to generate system-level requirements to eventually create specifications for each configurations item (CI). These specifications are then used by the design (or discipline) engineers to design and produce the CIs. The right side of the *"Vee"* represents the integration of these CIs to create the final system which is then verified and validated with the help of the qualification system that is created based on the needs of the stakeholders identified in the first step. The whole design process moves from left to right in time where iteration between the high- and low-levels is not only important but highly encouraged. The horizontal line depicts the point where information is handed-off from system engineers to respective discipline engineers who will produce the physical entity satisfying the given specifications. This line can be moved higher or lower to represent decreasing or increasing overlap between design and integration activities. For example, if

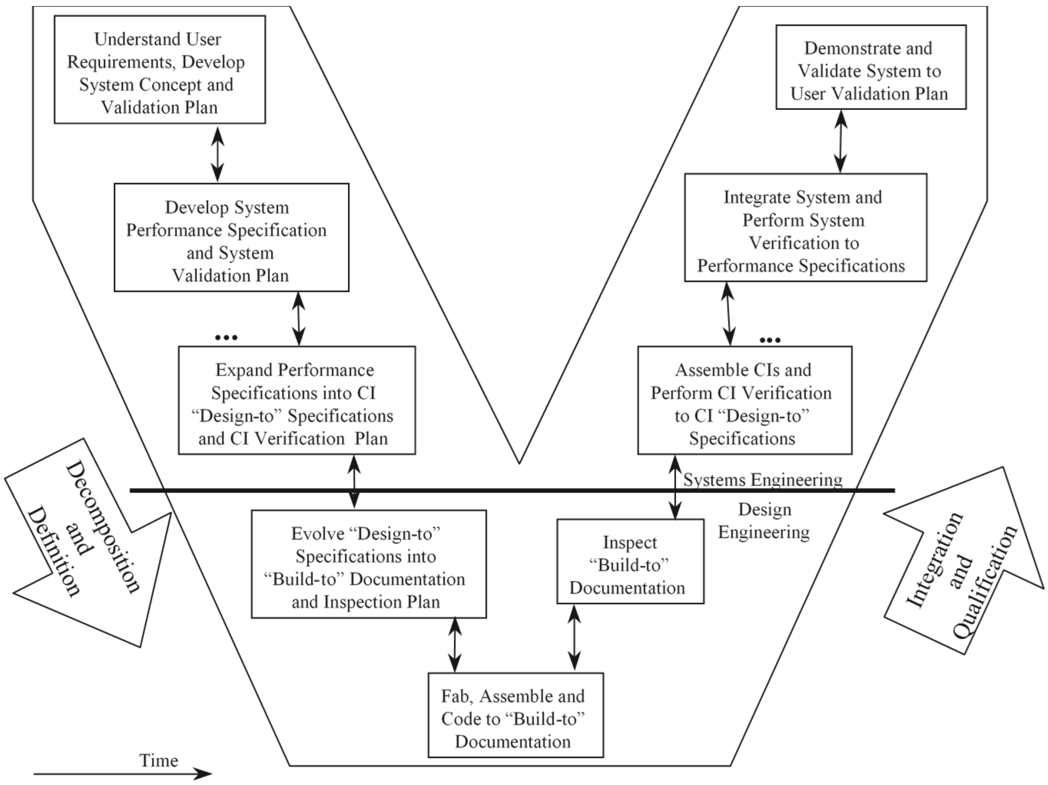


Figure 3.1. Systems Engineering "Vee" Diagram [48]

the horizontal line is draw above the intersection of the *"Vee"*, it means that there is no overlap between the design and integration activities. This could represent the contractual relationship between procurers and suppliers in the design process.

Now, in the following case study, we demonstrate that this model-based approach is not only capable of capturing the regulatory requirements but also identifies the appropriate design stages related to these requirements.

3.2 Healthcare Case Study

Healthcare industry is one of the most safety-critical industries where product designs are driven by different standards and regulations to a large extent. Therefore, we chose to demonstrate how regulatory requirements are expressed using a model-based representation of the design process of a healthcare device. This work has been done in collaboration with the INCOSE Healthcare MBSE Challenge Team [49], who are working with an aim to demonstrate the value of MBSE for biomedical-healthcare devices. The challenge team provided the expertise regarding the healthcare side of this case study.

3.2.1 Introduction

The challenge team has been working on creating a reference model for an infusion pump. U.S. Food and Drug Administration (FDA) defines infusion pump as *"a medical device that delivers fluids, such as nutrients and medications, into patient body in controlled amounts"* [50]. For the last few years, the Laboratory of Software Engineering at FDA has been working with various academic collaborators to develop model-based tools and verification techniques for infusion pumps. FDA believes that these model-based tools not only save costs and time but also make the design more robust and efficient as problems can be identified and resolved at early phases of design [50] [51] [52]. In our work, we adapted the model-based process representations described by Buede [23] in SysML diagrams to represent the system life cycle processes of an infusion pump. Moreover, we harmonized these representations with the following three standards:

1. ISO 15288: Systems and software engineering - System life cycle processes [53]
2. ISO 14971: Application of Risk Management to Medical Devices [54]
3. IEC 62366-1: Application of Usability Engineering to Medical Devices [55]

3.2.2 Process Diagrams

The system life-cycle process is represented with the help of SysML block definition, internal block and activity diagrams. All the diagrams are connected using a navigation page as shown in Figure 3.2. The diagrams on the navigation page are categorized into following three categories:

1. **Pre-Systems Engineering Processes:** The diagrams in this region represents the steps that occur before the start of the system-level design activities. This could be considered as the highest level of abstraction of the design process.

2. **System-level Design Activities:** The region marked in green contains diagrams for all the processes involved in the system-level design activities from problem definition to qualification system development.

3. **Mapping Information:** The process diagrams in the above categories are mapped to the sections and terminologies of ISO 14971:2007 [54]. This mapping works like a dictionary between SE and Healthcare terminology.

Examples from the Diagrams

A lot of process diagrams were generated to represent the design process. We discuss some of the process diagrams here but all the generated diagrams are compiled in the Appendix A. In the block definition diagram shown in Figure 3.3, we see all the activities (or steps) that are part of the *Development Phases* (highest-level of abstraction). The activity representing systems engineering is marked as our system-of-interest. The information flow diagram for these development phases (figure 3.4) shows the information flow across these steps. The information flow diagram consists of swimlanes that distribute the steps among different groups, namely, the stakeholders, the SE team, the discipline engineers and the qualification system discipline engineers, in the team. It should be noted that for a small design team, the same person can play more than one role in this diagram. Figure 3.5 provides an zoomed-in view of the inputs and outputs of the SE activity.

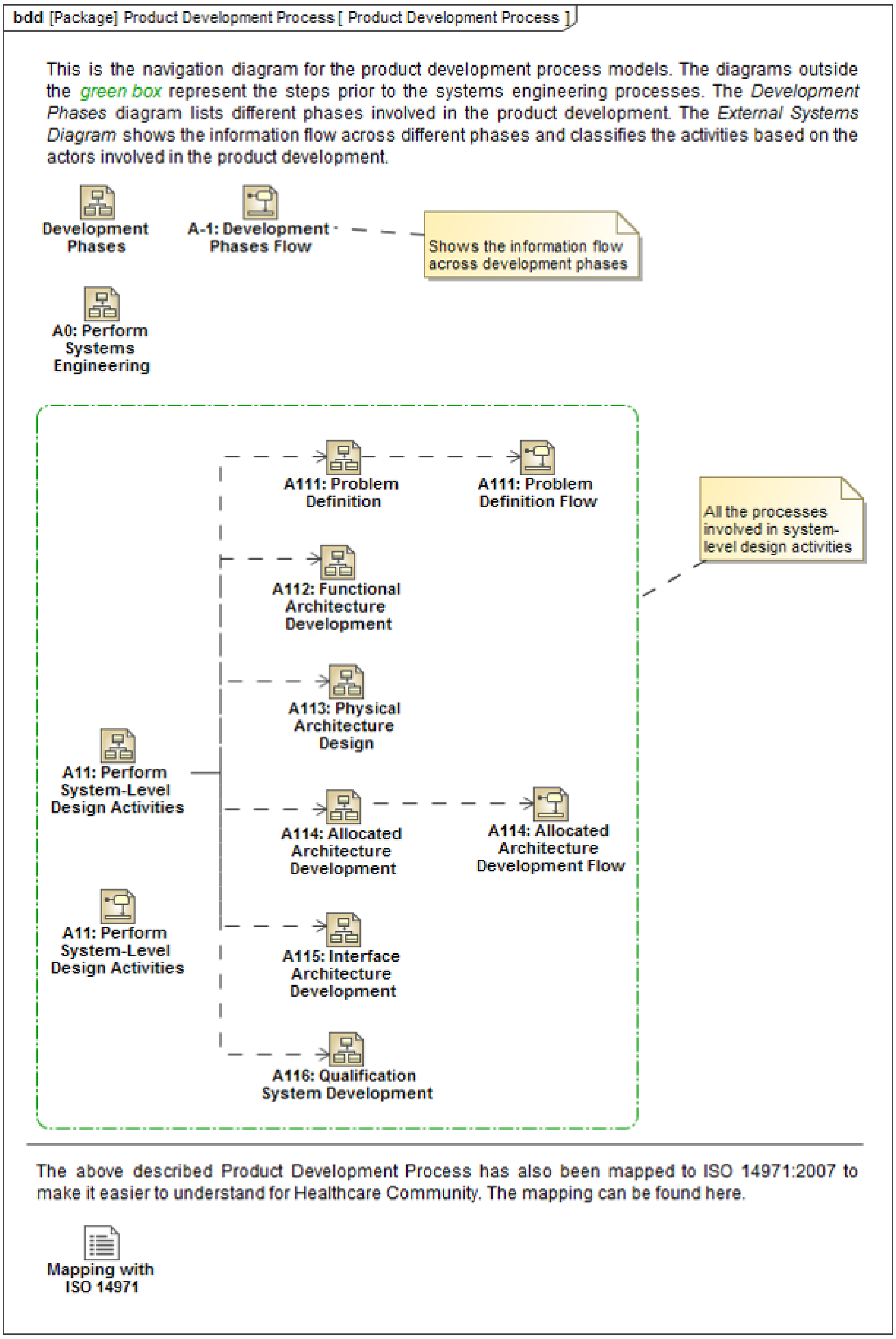


Figure 3.2. The Navigation Page

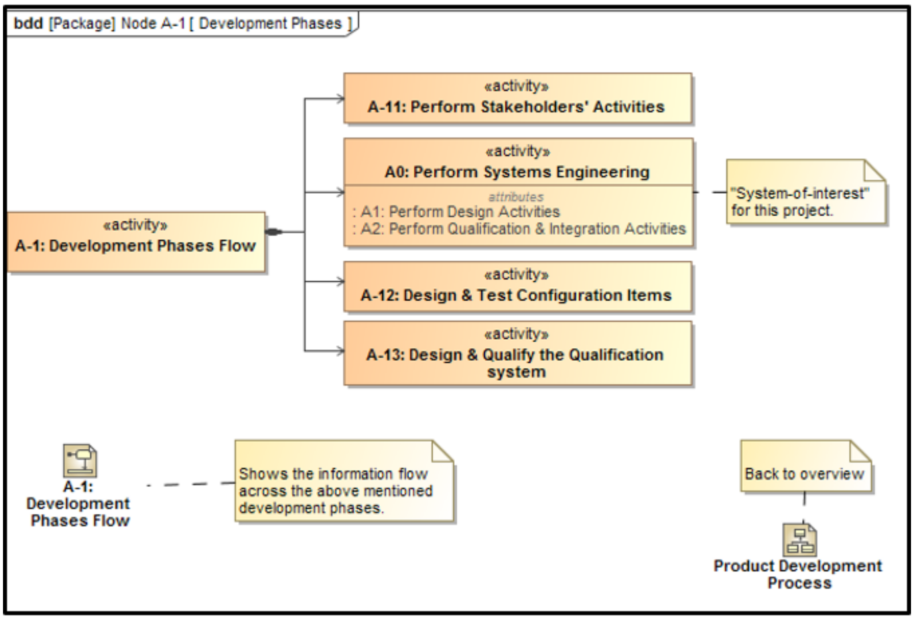


Figure 3.3. Development Phases - Block Definition Diagram

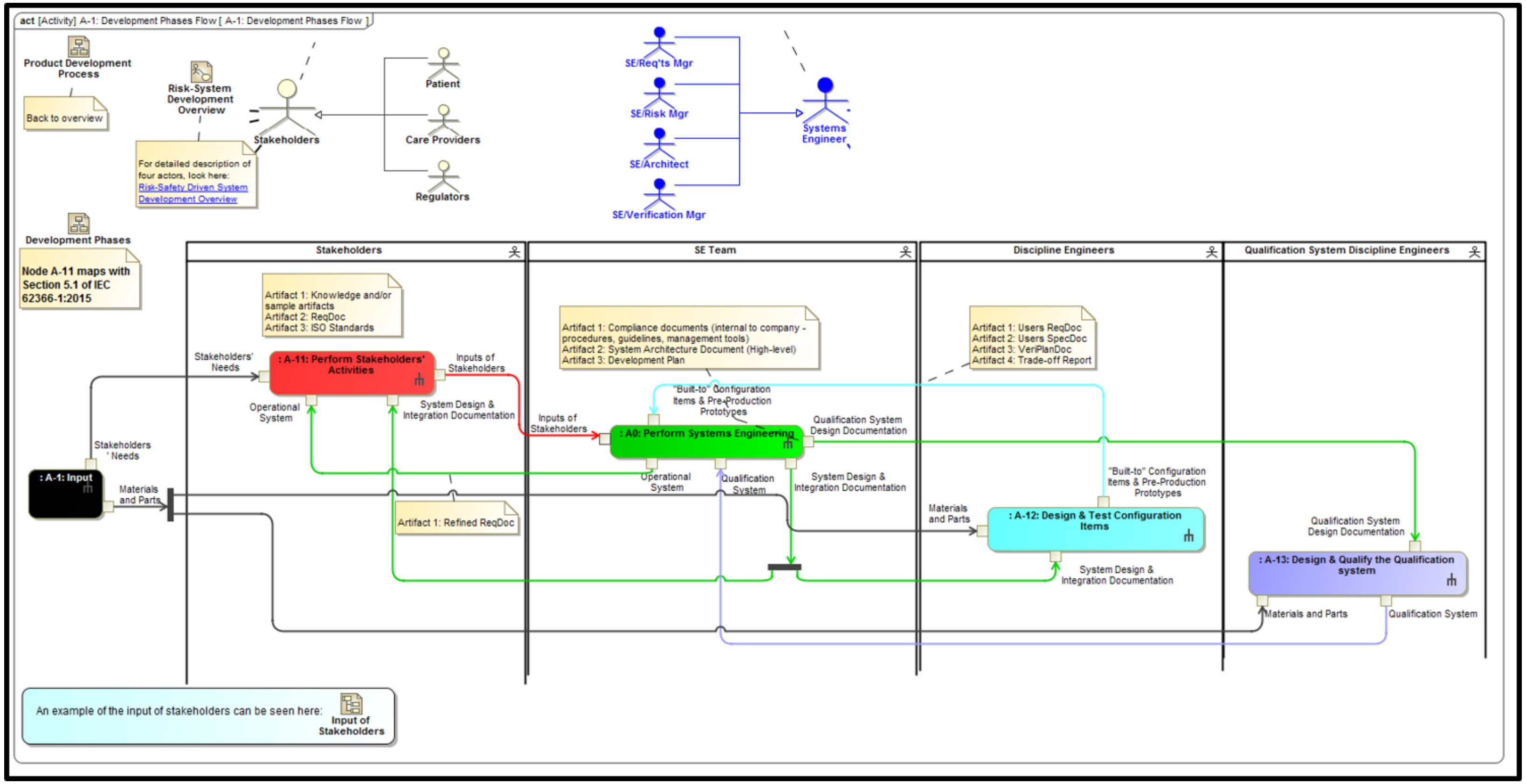


Figure 3.4. Information flow across different Development Phases

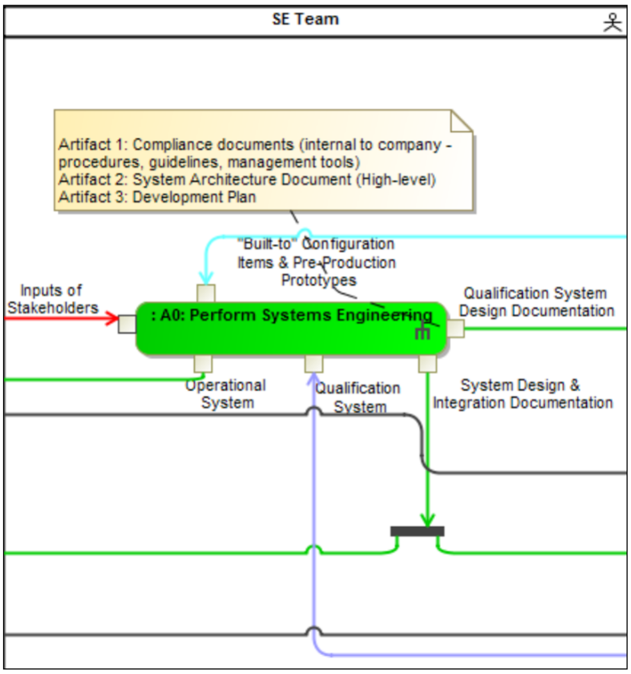


Figure 3.5. Perform Systems Engineering

Another example from the process diagrams is shown in Figure 3.6, where steps for *Allocated Architecture Development*, a system-level design activity, are represented. Some of these steps are further broken down in attributes that are mapped from ISO 14971 using the approach followed by Malins et al. [56]. Similarly, in the activity flow diagram (Figure 3.7), the specific section from IEC 62366-1 is mapped to relevant step using comments.

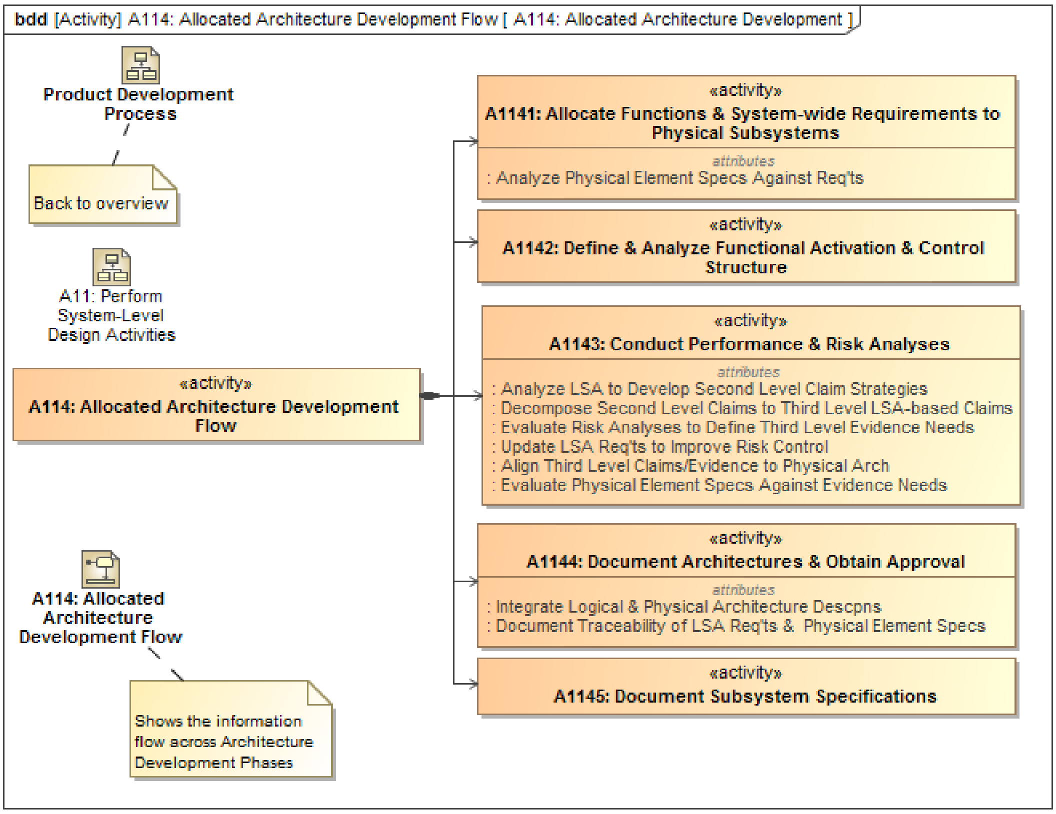


Figure 3.6. Allocated Architecture Development - Block Definition Diagram

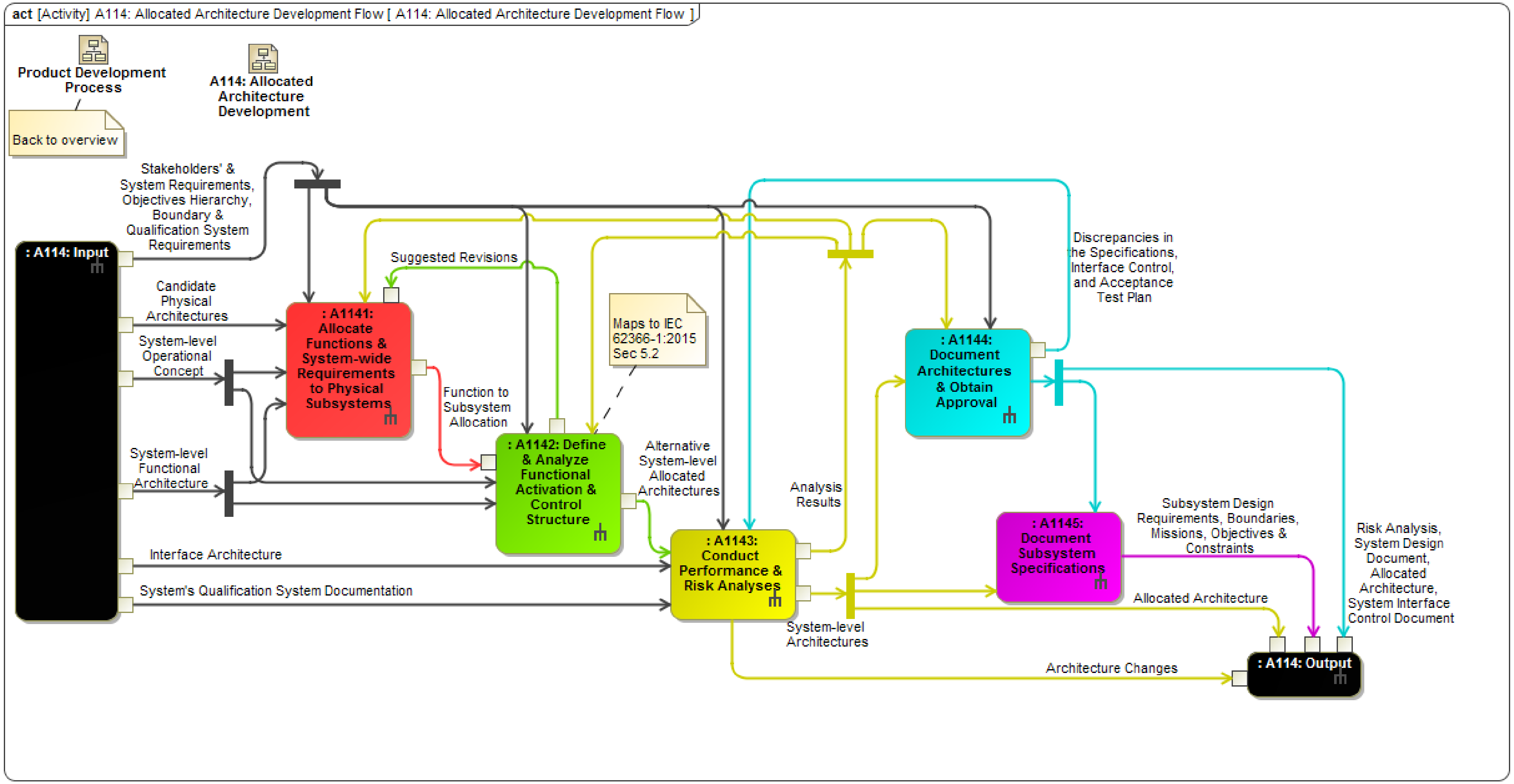


Figure 3.7. Activity Flow Diagram for Allocated Architecture Development

Content Diagram Product Development Process [Mapping with ISO 14971]

Mapping ISO 14971 to Buede's Diagrams

14971	Buede's Diagrams		
Risk Analysis Step	**Produced by**	**Part of Artifact**	**Feeds to**
Intended Use	A1111 Develop Operational Concept	System-level Operational Concept	
Identify characteristics related to safety	A1111 Develop Operational Concept	Preliminary Hazard Identification	System-level Operational Concept (using FDA guidance document, etc.)
	A112 Develop System Functional Architecture	Functional Hazards *(from use cases)*	System-level Final Architecture
	A113 Design System Physical Architecture	Physical Hazards *(from use cases)*	Physical Architecture
	A1142 Define & Analyze Functional Activation & Control Structure	Emergent Hazards from Activation & Internal Structure	Alternative-level Allocated Architecture
Risk estimation	A1143 Conduct Performance & Risk Analyses	Estimated Risks	Analysis Results
Risk Control	A1143 Conduct Performance & Risk Analyses	Risk Controls, Option Analysis	Architecture Changes
Risk Management Report	A1144 Document Architectures and Obtain Approval	Risk Evaluation in Risk Management Report	Risk Analysis

Notes:
- Stakeholder's constraints in A111 are the user constraints for the healthcare domain. (Think about the patient).
- Regulatory bodies' constraints mostly feature in the Qualification constraints from IEC 62366-1, ISO 14971, ISO 15288, etc.

Figure 3.8. Mapping Buede's diagrams with ISO 14971

Finally, figure 3.8 summarizes the mapping of ISO 14971 to different activities in the model-based process representations. This kind of mapping table not only serves as a *Rosetta Stone* between system engineers and other domain experts (here, Healthcare) but also traces the regulatory requirements to specific design steps making the design process more efficient and robust.

3.3 Lessons Learned

In this chapter, we adapted the model-based process representations, given by Buede, to represent the product design process of a biomedical device. We observed that the model-based approach not only manages to capture the regulatory requirements but also map them to specific design activities. The identification of the stages where a standard is being used makes the design process more efficient and robust from the perspective of compliance activities. The method of creating the mapping tables also serves as a means to communicate the SE knowledge to other domains.

4. UAV Design Case Study

In this chapter, we apply the product design approach explained in the chapter 3 to an unmanned aerial vehicle (UAV) design process. We will also adapt the translation framework, developed in the chapter 2, to connect the model-based representations with another analysis tool, XFOIL [57].

4.1 Introduction

The US Department of Defense defines UAV as *"a powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload"* [58]. Today, the UAVs are used for both military and non-military purposes including search and rescue operations, forest fire detections, acrobatic aerial footage in film-making and leisure flying. Consider the design process of one such UAV, which is planned to be used as the first responder during emergency conditions. The UAV is supposed to gather information about the emergency site until emergency personnel arrives on scene.

4.2 System-level Design Activities

Now, we follow the SE process, shown as the system-level design activities in the chapter 3, to design the UAV.

4.2.1 Problem Definition

Based on the figure 3.2, the first step in the design process to define the problem. After identifying the need, it is important to capture the important requirements as

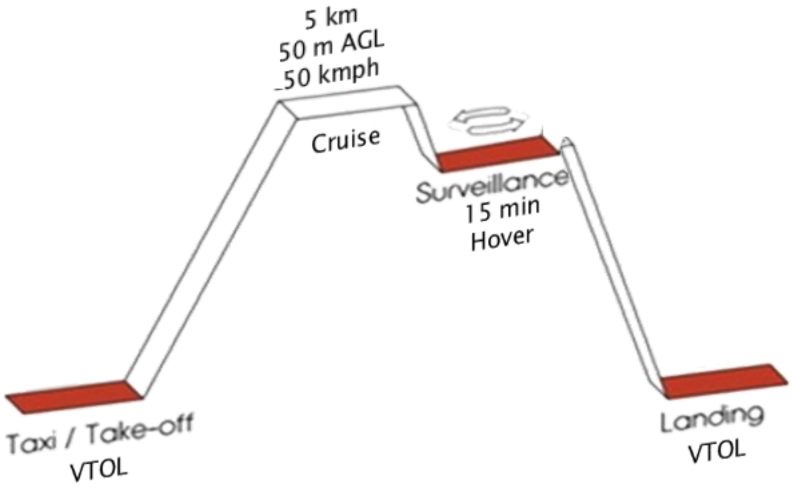


Figure 4.1. Mission Scenario

these requirements will work as the foundation for the whole design process. It is also important to have solution neutral requirements to avoid introducing artificial limitations. In our case, the mission of the UAV can be defined as: *"To design a rapid deployable UAV first responder to the scene of an emergency while Police, Fire, and Medical teams are en route"*. A mission scenario, which has been defined by the stakeholders in the pre-SE processes, is shown in the Fig. 4.1. Based on the given information, the most important requirements for this UAV can be depicted in the model-based representations, as shown in Fig. 4.2.

4.2.2 Functional Decomposition

The next step after properly defining the problem is to decompose the system into different components (or subsystems) based on their functions. It is advisable to name the components, based on their functions, rather than the physical component associated with it. For example, instead of *propellers*, the component is named as *thrust system*. This method of classifying and naming components not only keeps the process solution neutral but also makes it easy to determine the impact of changing

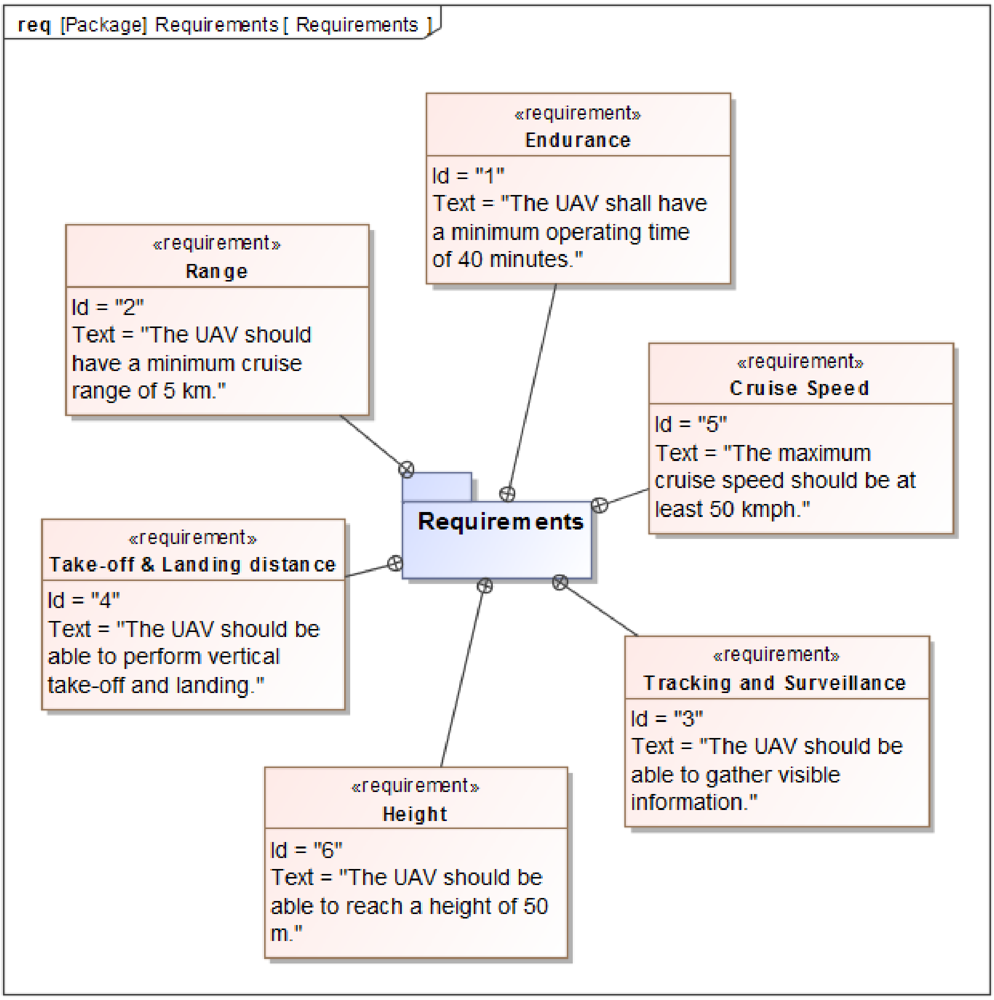


Figure 4.2. Model-based Representation of the Requirements

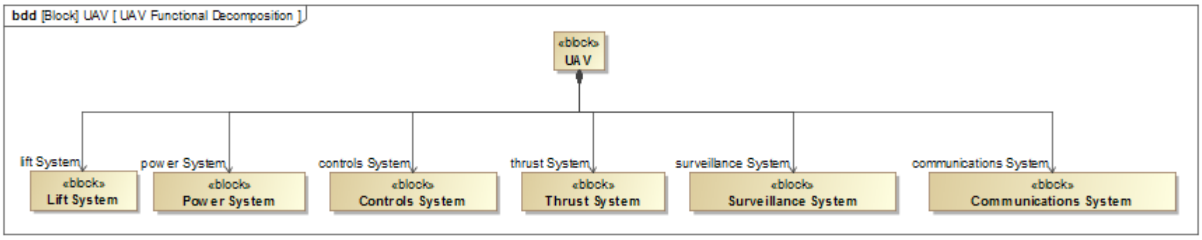


Figure 4.3. Functional Decomposition of the UAV system

the physical component through the model traceability. An example of functional decomposition for our system is shown in Fig. 4.3.

4.2.3 Physical Architecture Design

Once the functional decomposition is completed to enough detail, the development of the physical concepts that will satisfy the given functions start. Now, the design of these physical concepts can be a very complex process involving further decomposition and this is where the horizontal line in the *"Vee"* diagram (Fig. 3.1 is drawn. For example, in our system, the *Lift System* can have either *Wing* or *Rotors* or a combination of both as possible physical concepts. Moreover, as shown in the Fig. 4.4, the *Wing* can be further broken down into different types: *Fixed Wing* and *Folding Wing*. Our final concept design will consist of any one (or a combination) of these physical concepts.

4.2.4 Architecture Allocation

Once a number of physical concepts are generated, the next step is to analyze and allocate the most suitable architecture, based on the performance metrics. The detailed steps for this activity are shown in the Fig. 3.6. For example, in our case, the best *Fixed Wing* can be selected based on its *Airfoil* and *Structural* characteristics

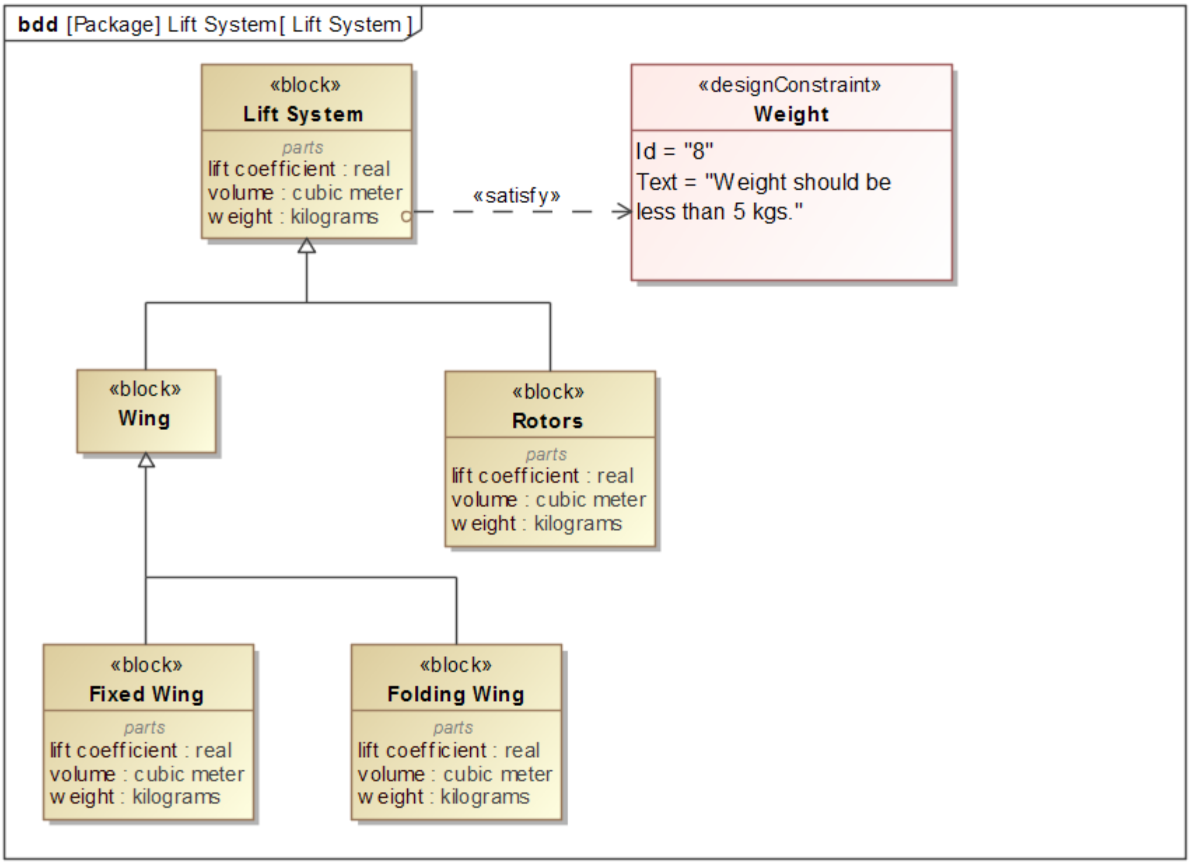


Figure 4.4. Physical Architecture for the *Lift System*

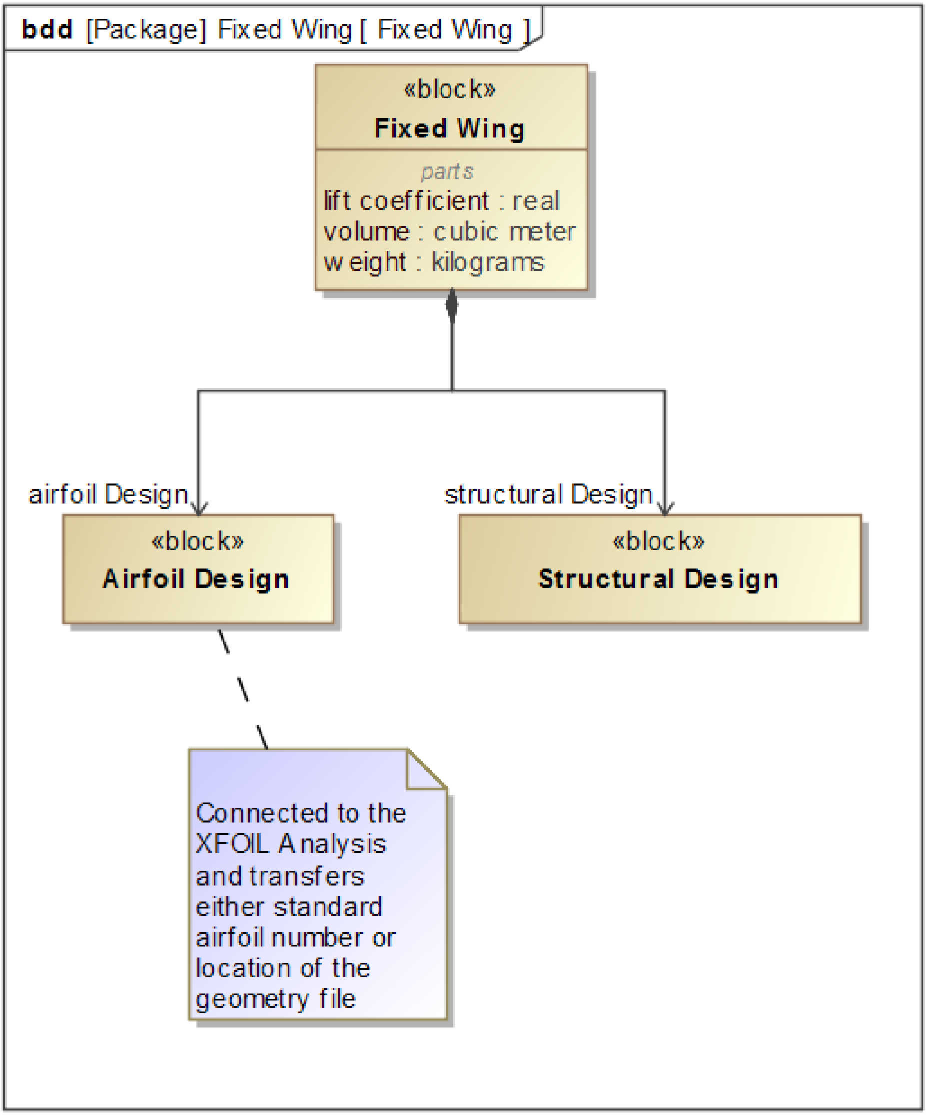


Figure 4.5. Decomposition of Physical Design of a Fixed Wing

(Figure 4.5). We will see how the analysis tool (XFOIL) is connected to the airfoil analysis in the next section.

4.2.5 Interface Architecture Development

After allocating the physical concepts based on the functional decomposition, we develop the architecture for the interaction between the components. This step is crucial to identify the critical components in the design and make sure that the allocated physical components are compatible with each other. For example, in our design, at this step, the interface between the *thrust system* and *lift system* will be developed, i.e., we will understand the interaction between the propellers and the fixed wing.

4.2.6 Qualification System Development

The final step in the design process is to verify that the designed system satisfies the requirements created in the beginning. In this step, we develop the qualification system that will perform this check on the final design. For example, for the UAV design, we might have to perform a timed test flight to show if our final design can fly for 40 minutes.

4.3 Airfoil Analysis using XFOIL

In this section, we will explain how we can modify the translation framework, explained in the chapter 2, to connect model-based representations with any analysis tool. We demonstrate the modified framework by enabling the translation from model-based representations to XFOIL, a low-fidelity aerodynamic analysis tool.

In chapter 2, one of the challenges with the translation framework (Fig. 2.5) is that every pair of domain specific toolboxes require a different translator. Due to this shortcoming, even though the framework provides a guideline towards solving the challenge of connecting the MBSE representations with analysis tools, its proper implementation is still a daunting task. To address this challenge, we propose a slight modification to the framework (see Fig. 4.6). We observed that due to the popularity of computational tools like MATLAB®, Python, etc., a number of important analysis tools are already interfaced with these tools [59]. In fact, The MathWorks Inc. has been releasing comprehensive documentation on how to interface external tools with MATLAB® [60]. So, if we can enable the translation of MBSE representations to

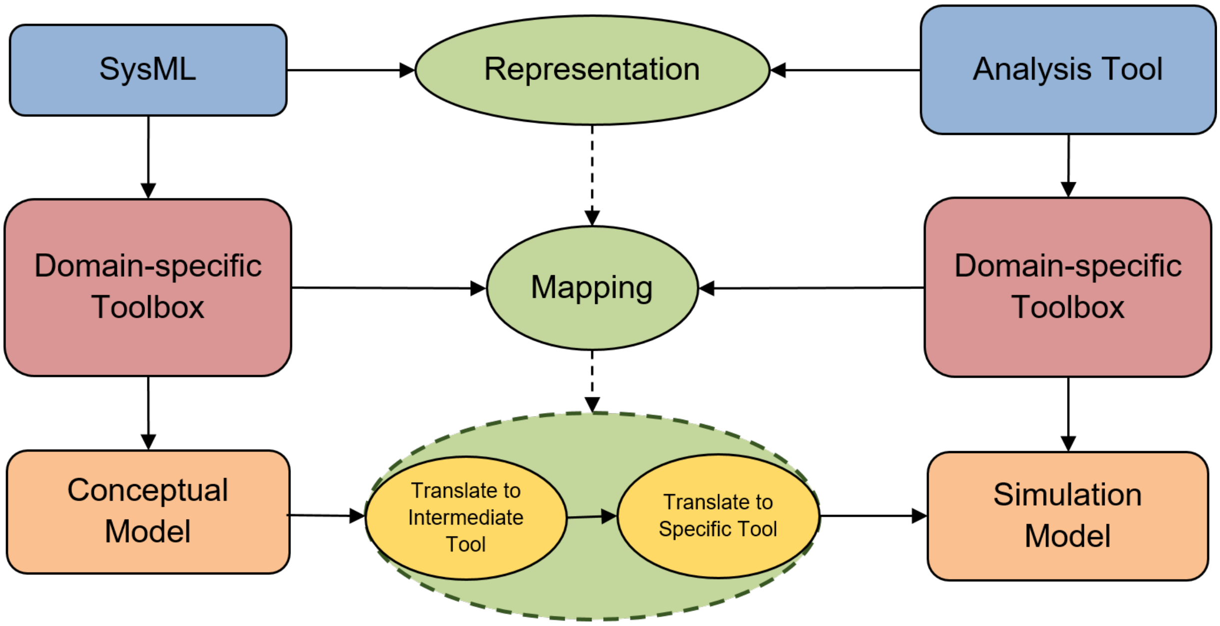


Figure 4.6. Modified Translation Framework

these popular computational tools (*intermediate tool*), we will be able to enable the translation to a number of analysis tools (*specific tool*). We demonstrate the modified translation framework in the following section.

4.3.1 Demonstration

During *Architecture Allocation* (section 4.2.4), *Conduct Performance and Risk Analyses* is one of the most important step as the results of this analysis will determine which concept will be selected for the final design. For example, in the UAV example, the design process of a *Fixed Wing* can be further divided into *Airfoil Design* and *Structural Design* (Fig. 4.5. Now, we perform the airfoil analysis using XFOIL.

Say, we want to perform an aerodynamic analysis of *NACA 24012* airfoil for our UAV. The analysis can be done in the following three steps:

```
%% Create a NACA 5-series airfoil
xf.Airfoil =  Airfoil.createNACA5('24012',150);
% To create a NACA 4-series, use   >> xf.Airfoil =  Airfoil.createNACA4('0012');
% To load an existing airfoil, use >> xf.Airfoil =  Airfoil('naca0012.dat');
```

Figure 4.7. Snippet from the generated MATLAB file

1. We transfer the information about the airfoil geometry (standard NACA 5-digit series number here) to MATLAB with the help of the translator developed in the chapter 2. Figure 4.7 shows a snippet of the generated MATLAB file after the translation.

2. Next, we use the MATLAB-XFOIL interface developed by Rafael Oliveira to perform the aerodynamic analysis [61]. Figure 4.8 shows a snapshot of the XFOIL analysis.

3. Figure 4.9 shows the generated results for various aerodynamic parameters. We can select and feedback values to the MBSE model as per our requirements.

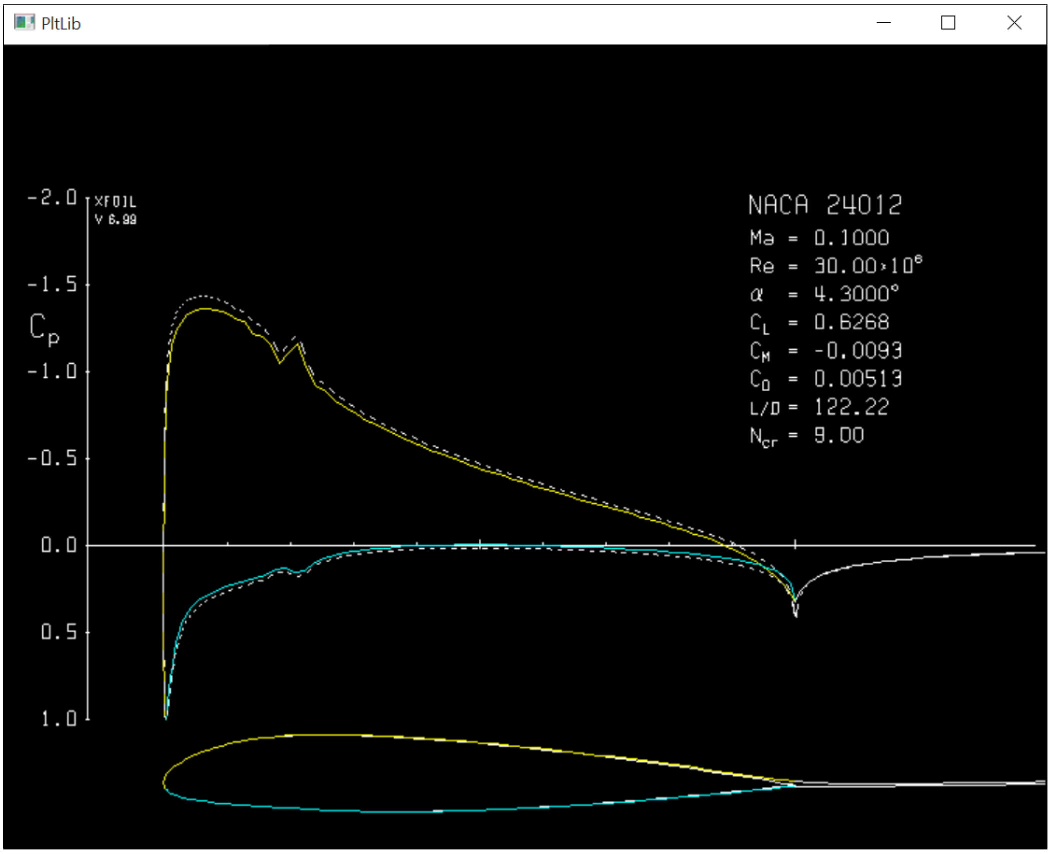


Figure 4.8. Snapshot of the XFOIL Analysis

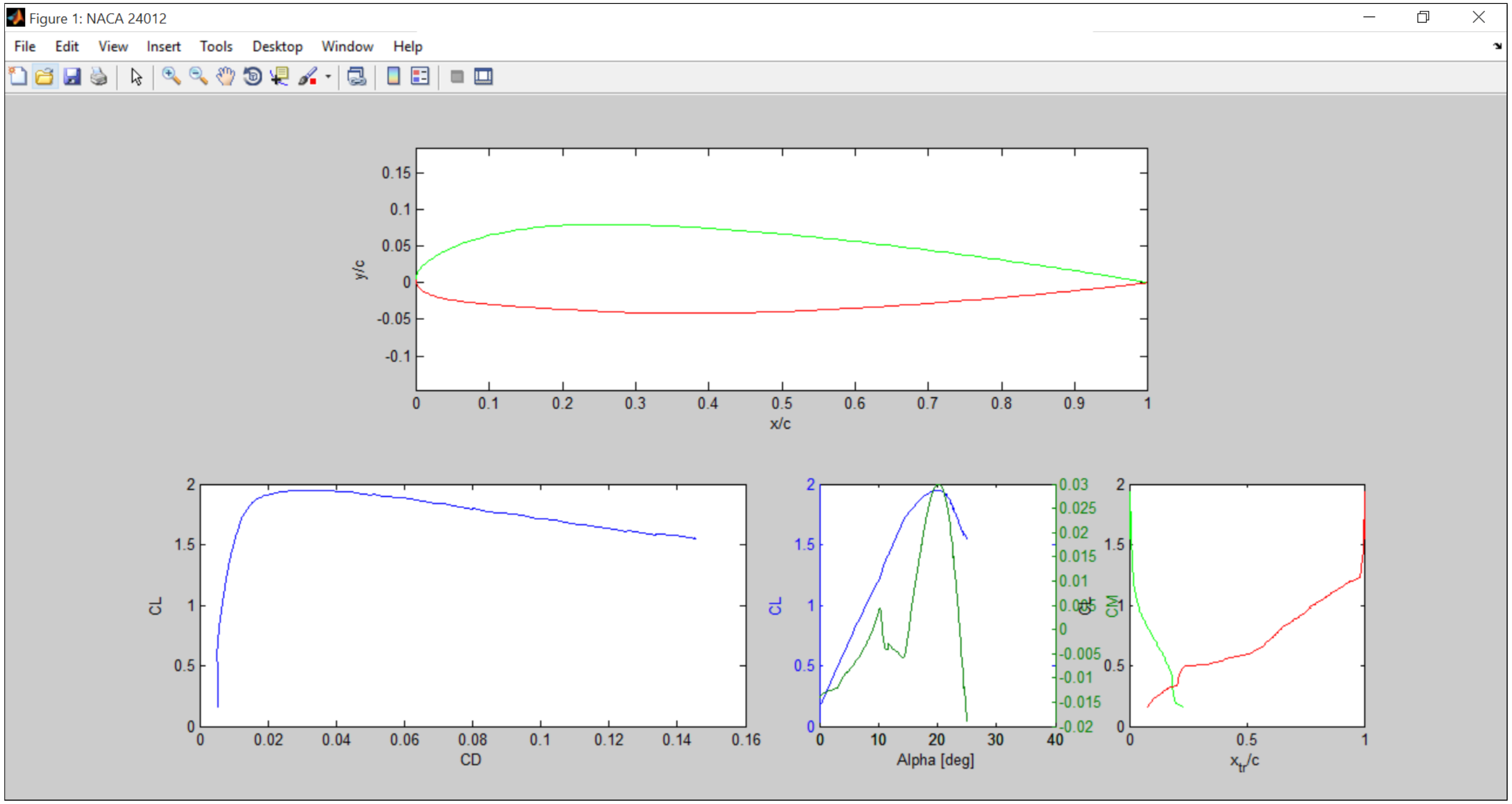


Figure 4.9. Final XFOIL Analysis Results

4.4 Lessons Learned

In this chapter, we showed how the Buede's process representation diagrams that were used to represent the product design process of a biomedical device can be used to describe the design process of a UAV. With the help of UAV case study, we also demonstrated how the translation framework that was introduced in the Chapter 2 can be adapted to implement it to other analysis tools. The third step of *translation* from the conceptual model to the simulation model was broken into two steps, where, first the conceptual model is translated to an intermediate popular tool and then the existing interface between the intermediate and the analysis tool is used to translate to the simulation model. This additional step makes the translation to the analysis tool more efficient.

5. Conclusions and Future Work

5.1 Conclusions

This thesis outlines the advantages of MBSE and identifies the major roadblocks in its industrial adoption. With the help of three case studies, the author has suggested ways to handle two of these challenges. Although the answers to the research questions have been explained in detail throughout the document, we summarize them here:

- *What are the features of an effective framework for translating model-based conceptual representations to analysis models?*

  In Chapter 2, the author proposes a translation framework that enables the translation from a SysML conceptual model (created using MagicDraw) to an executable agent-based simulation model. The translation framework was also demonstrated using a simplified air transportation problem where three aircraft, communicating only using ADS-B, had to maintain a minimum separation distance. Along with the demonstration, a number of challenges were also identified that might hinder the implementation of the framework to a real world complex problem. In Chapter 4, the author proposes a modification to the framework to address one of the identified challenges. The modified framework was demonstrated using an airfoil analysis problem.

- *What are the specific products in a typical model based representation that, when properly formed, could be used to satisfy the regulatory requirements? And do these model based representations provide any benefit over the document-based approach?*

  In Chapter 3, Buede's systems engineering diagrams were adapted to represent the product design process of a biomedical device. Three standards, namely, ISO 15288, ISO 14971 & IEC 62366-1, were also harmonized with the representations to demonstrate that the model-based representations not only capture the regulatory requirements but also show the stages (in product lifecycle) where a specific standard will be used. Thus, it makes the design process more efficient and robust with respect to the regulations.

Overall, it was shown that the MBSE representations are capable of capturing the processes involved during the product lifecycle efficiently. Moreover, a translation framework was proposed to move towards the integration of MBSE with PLM.

5.2 Future Work

In this work, in addition to identifying and demonstrating strategies towards industrial adoption of MBSE, we also identified the challenges associated with it. Establishing the link between the model-based design representations and the analysis tools is crucial for the integration of MBSE & PLM and this work just describes the initial steps. Some of the future directions, categorized as short-term and long-term, are described in the following subsections:

5.2.1 Short-term

1. **Scalable Translation:** At the current stage, the translation to an agent-based simulation model works fine when the model-based representation does not contain a large number of occurrences of the same (or similar) element(s). But since design reuse is one of the main advantages of MBSE, it is really important to make the translation framework scalable for multiple occurrences of the same element.

2. **Coarse Graining:** As the same model-based representation can be connected to a number of analysis tools to perform different design evaluations, it is critical to be able to identify and extract the *"relevant"* information from the repre-

sentation. With an increase in the complexity of the systems, it is essential to manage models to retain the important information and in doing that, discovering what is important is the biggest challenge. To tackle this challenge, understanding the development of the Computer-Aided Engineering (CAE) tools, where information is extracted from CAD models to perform different engineering analyses, can be a good place to start.

3. **Interface Standards:** There is a need to standardize the information exchange between different analysis tools. These standards can boost the usefulness and interoperability of the tools. For example, the development of ISO 10303, informally known as *STEP*, has worked wonders for the CAD industry.

4. **Impact on Cognitive Load:** Another interesting area is to explore the impact of MBSE on the cognitive load of the design engineers. The richer and high-fidelity representations should not only make the design process more efficient but should also make it easier for the interdisciplinary teams of design engineers to interact and understand each other.

5. **Link with the Downstream Phases:** In our work, we mainly talk about the link between the model-based design representations and the analysis tools but we also need to establish the links with the downstream phases, such as manufacturing, product sustainability, etc., as well to make the model-based approach more relevant to the design process.

5.2.2 Long-term

1. **Dissemination of SE knowledge:** The difference in the vernacular terminology is the biggest hurdle in the application of SE to different domains. As described using the *mapping table* (Figure 3.8) in the Chapter 3, we mapped the information from SE to the corresponding Healthcare terminology. Creating

similar lexicons, with the help of domain experts and systems engineers, is vital to handle the increasingly interdisciplinary nature of the products.

2. **MBSE-PLM Integration:** To realize the maximum benefit from the model-based approach, it is very important to integrate the MBSE with the PLM. Currently, all the PLM tools are mainly managing the various documents (for example, spreadsheets, checklists, etc.) used throughout the lifecycle of the product. The next generation PLM tools must itself be *model-based* by incorporating more structured information with meaning and should follow a stronger model-based approach than they do today. The MBSE-PLM integration will not only boost the adoption of MBSE in the industry and but will also make the PLM tools more functional and thus, will lead us to a more efficient design process of the future.

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APPENDICES

A. SysML diagrams for the Healthcare Case Study

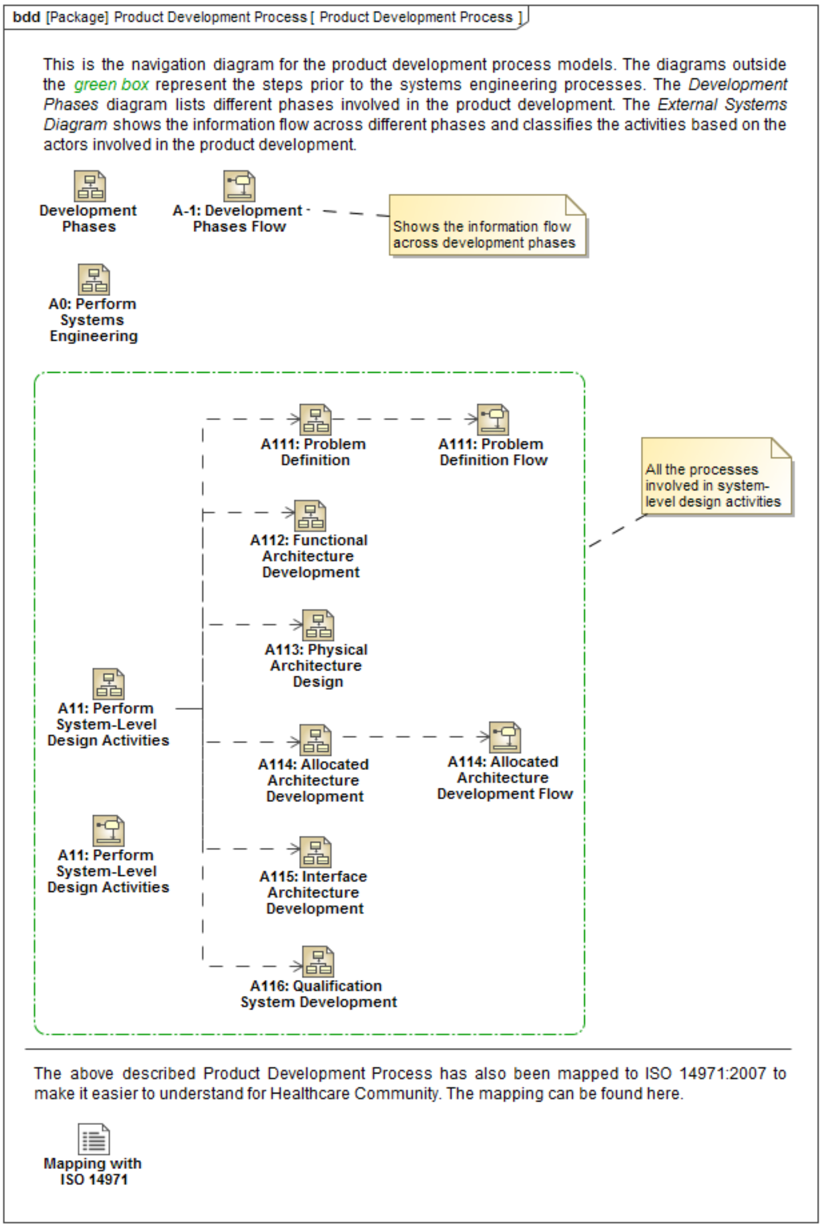

Figure A.1. Main Navigation Page

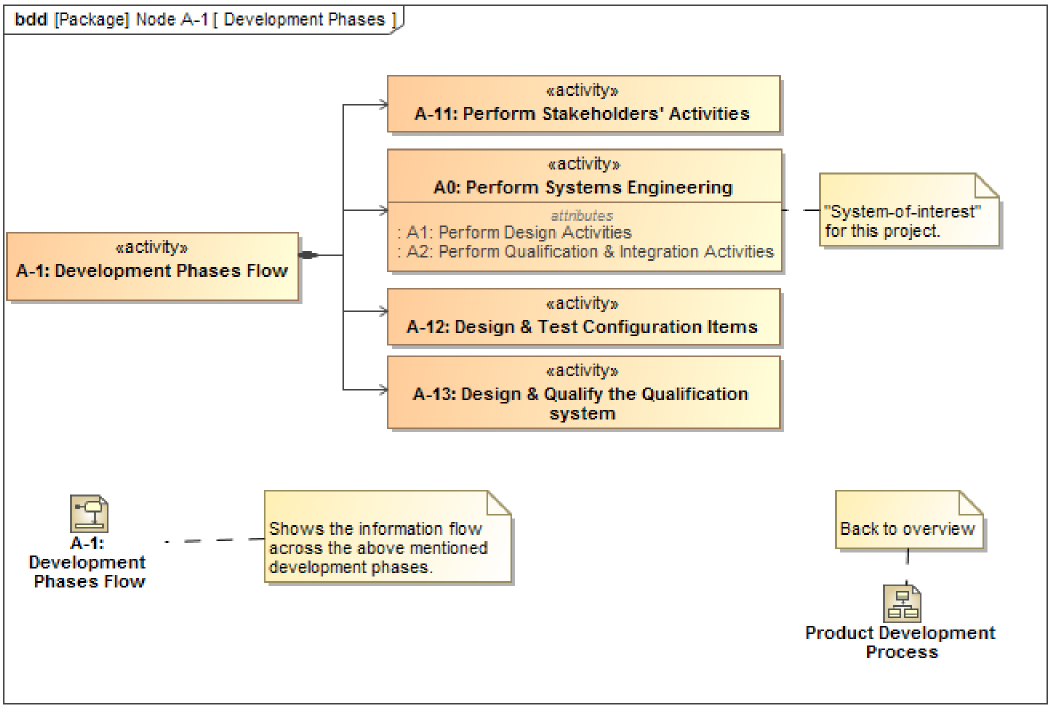

Figure A.2. Block Definition Diagram of the Development Phases

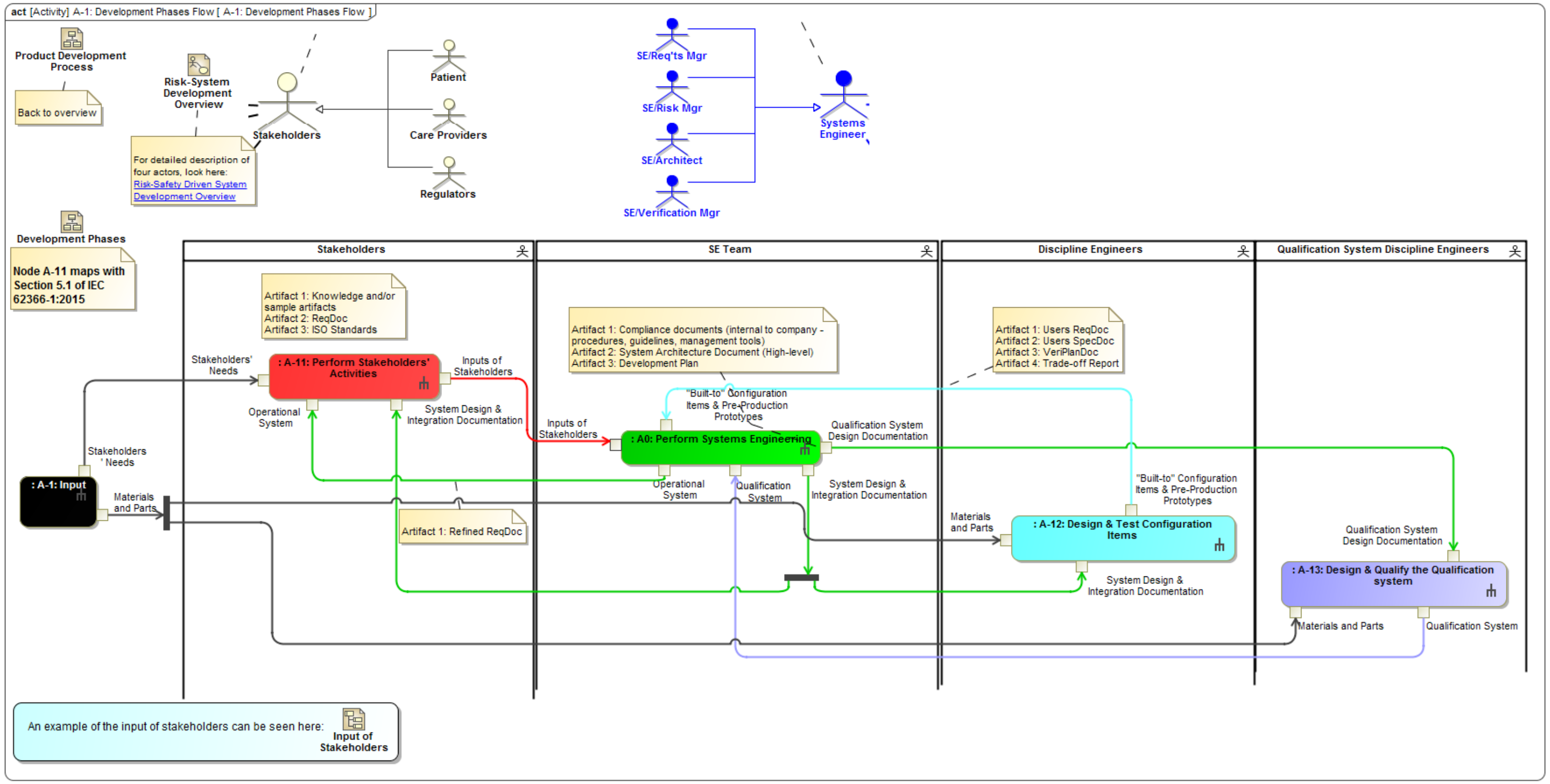

Figure A.3. Information Flow Across the Development Phases

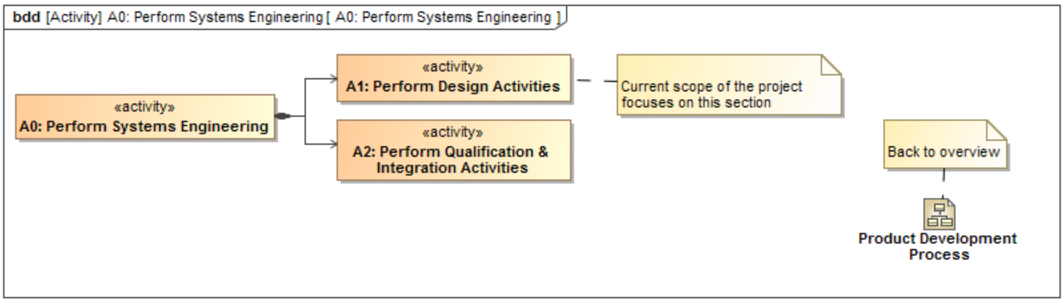

Figure A.4. Perform Systems Engineering - Block Definition Diagram

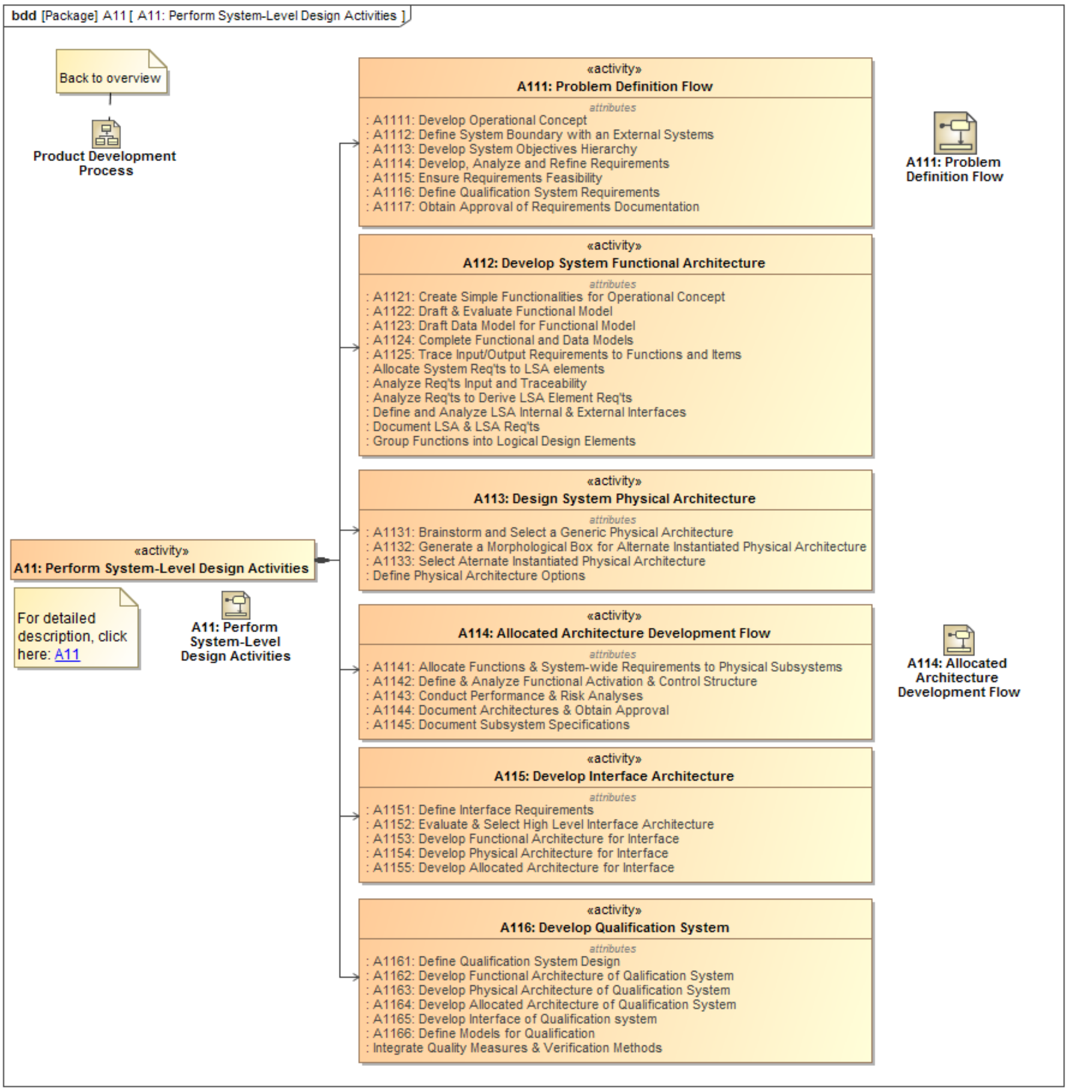

Figure A.5. System-level Design Activities - Block Definition Diagram

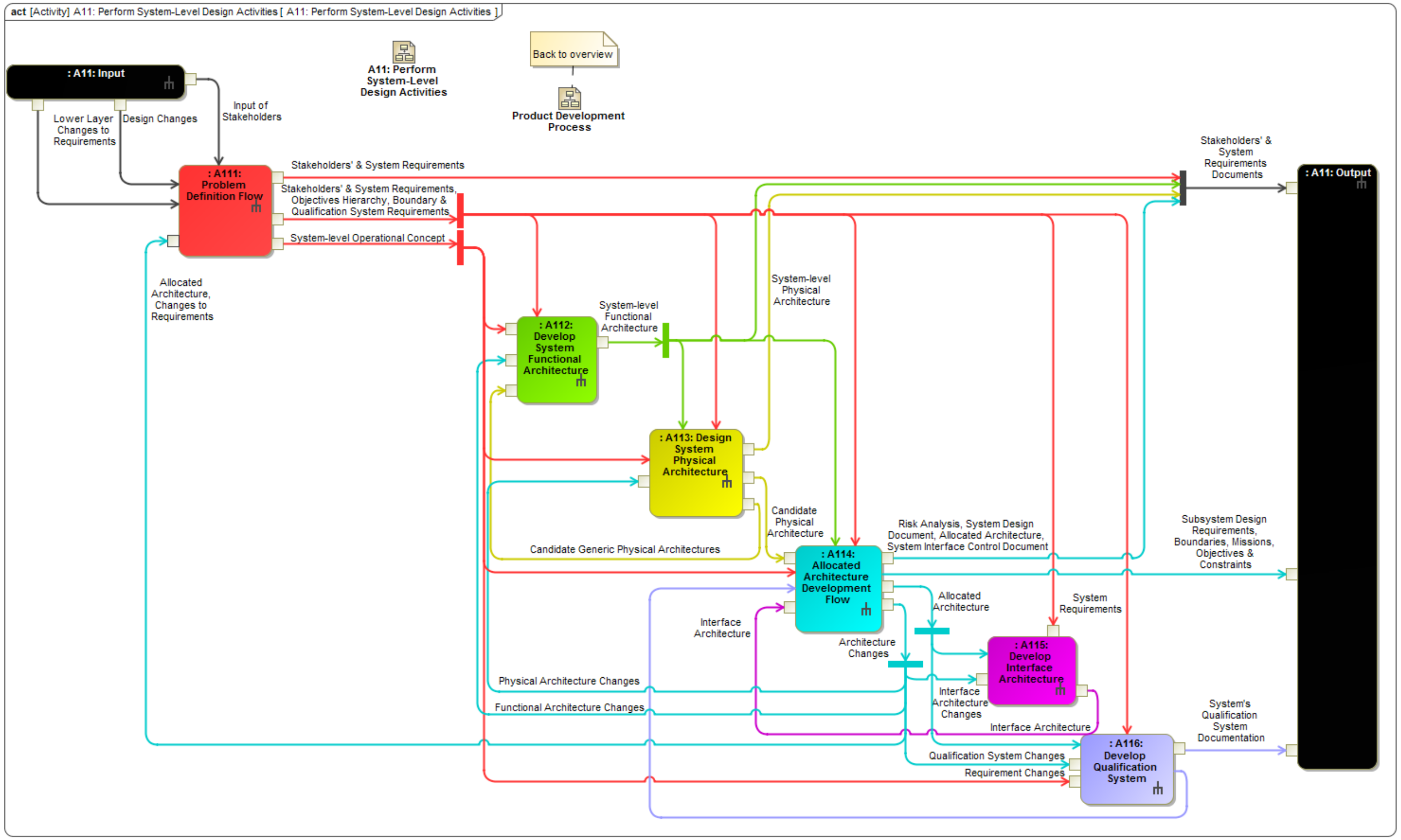

Figure A.6. Information Flow Across System-level Design Activities

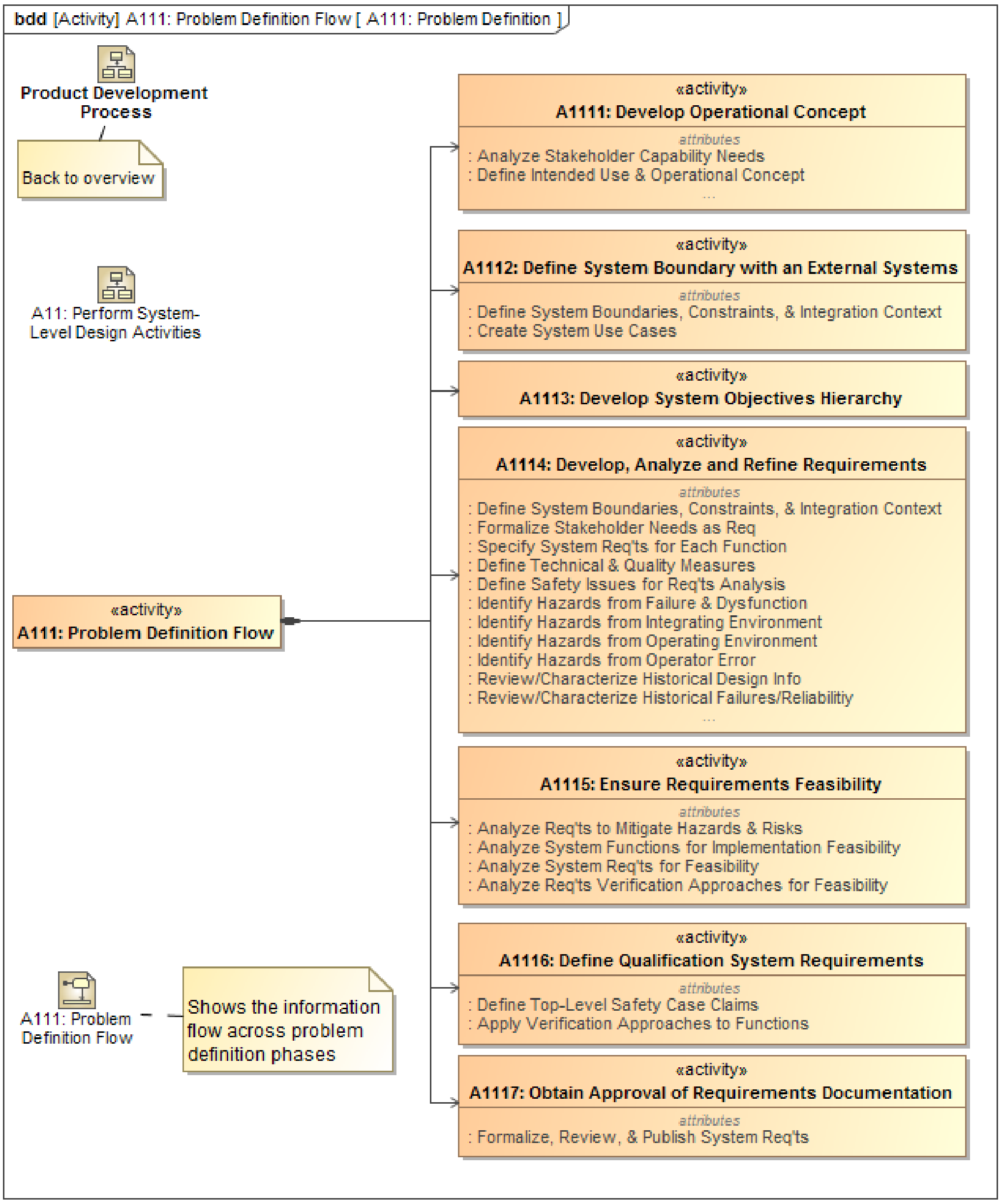

Figure A.7. Problem Definition - Block Definition Diagram

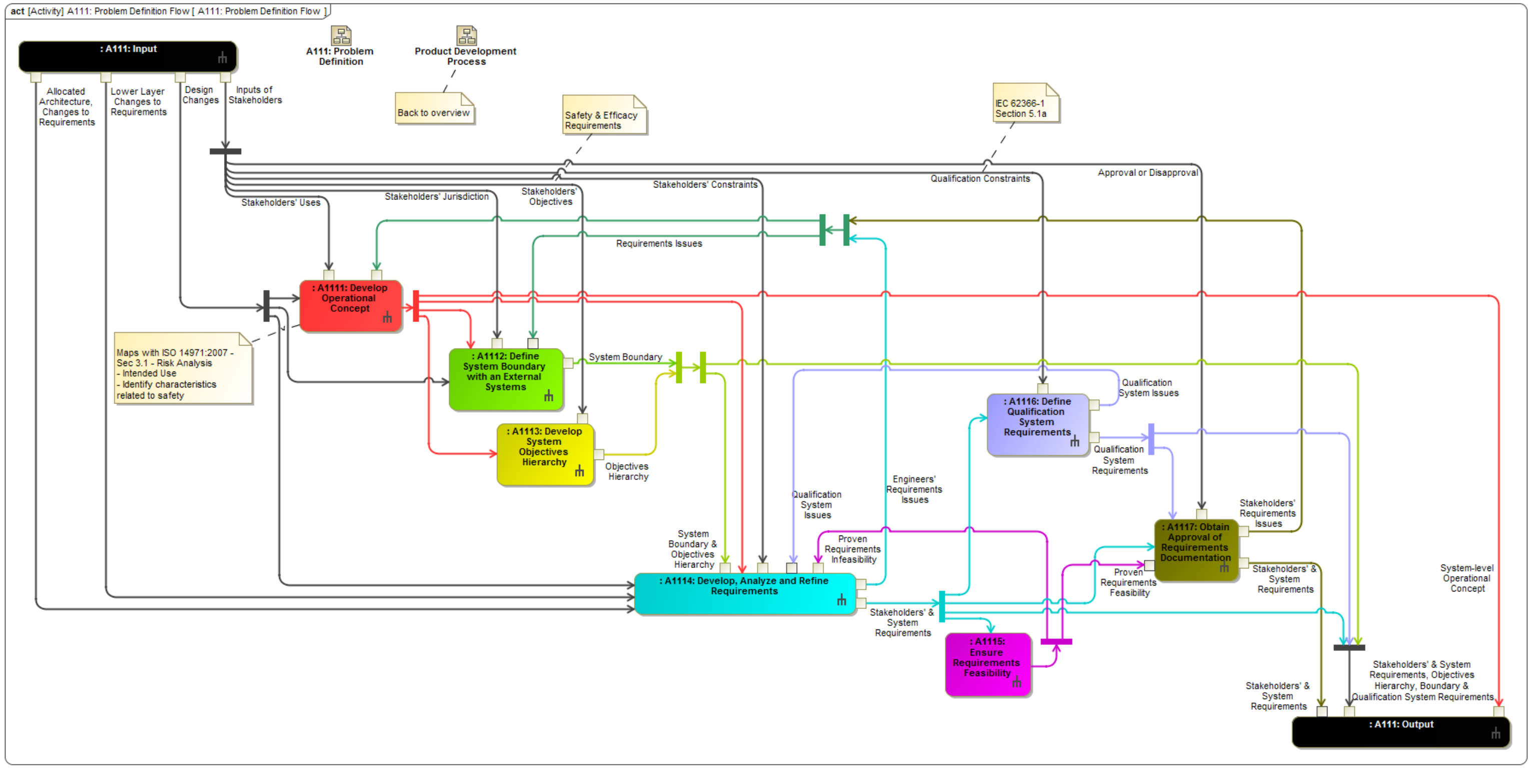

Figure A.8. Information Flow During Problem Definition

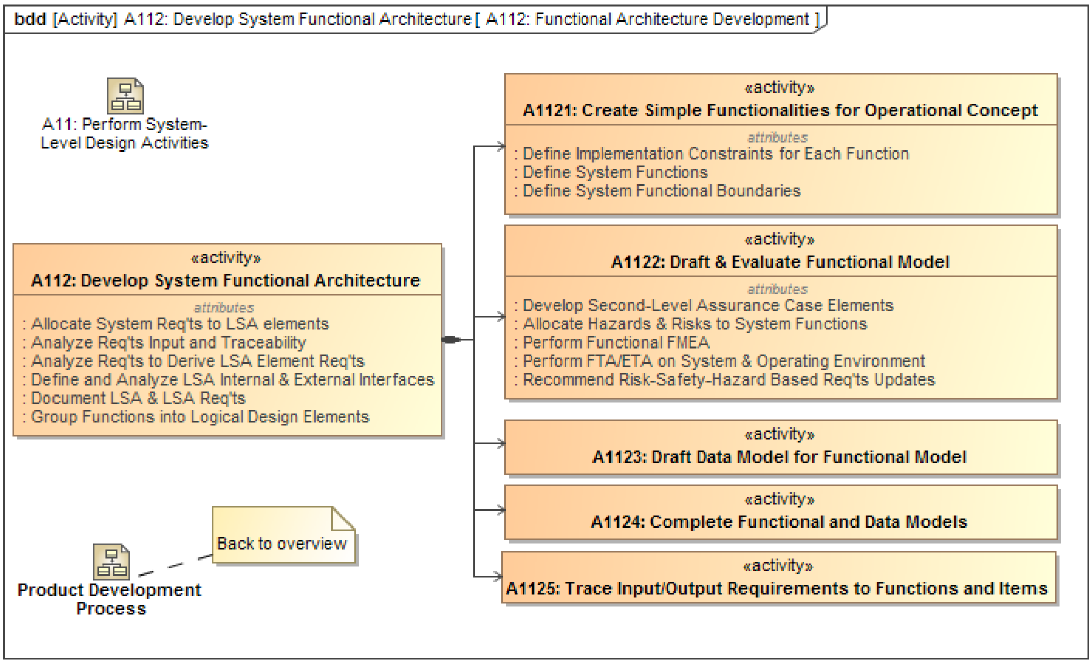

Figure A.9. Functional Architecture Development - Block Definition Diagram

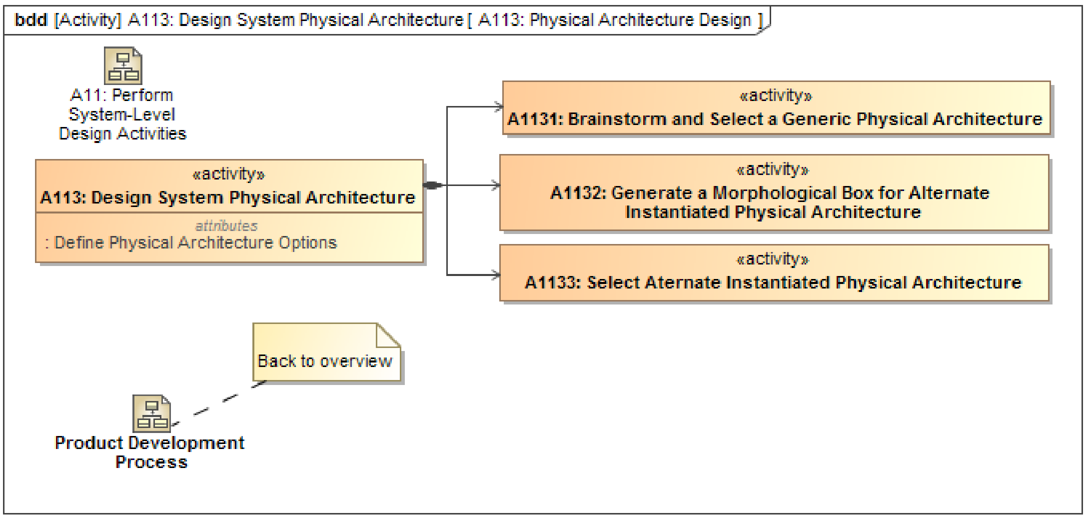

Figure A.10. Physical Architecture Design - Block Definition Diagram

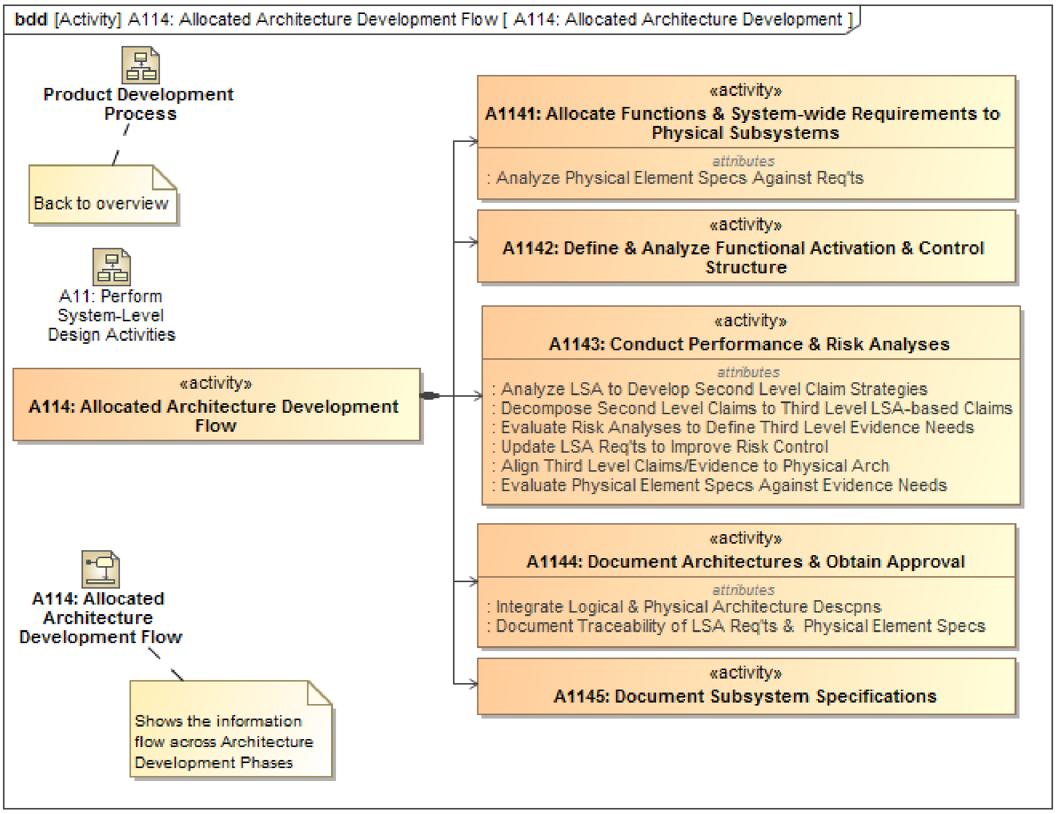

Figure A.11. Allocated Architecture Development - Block Definition Diagram

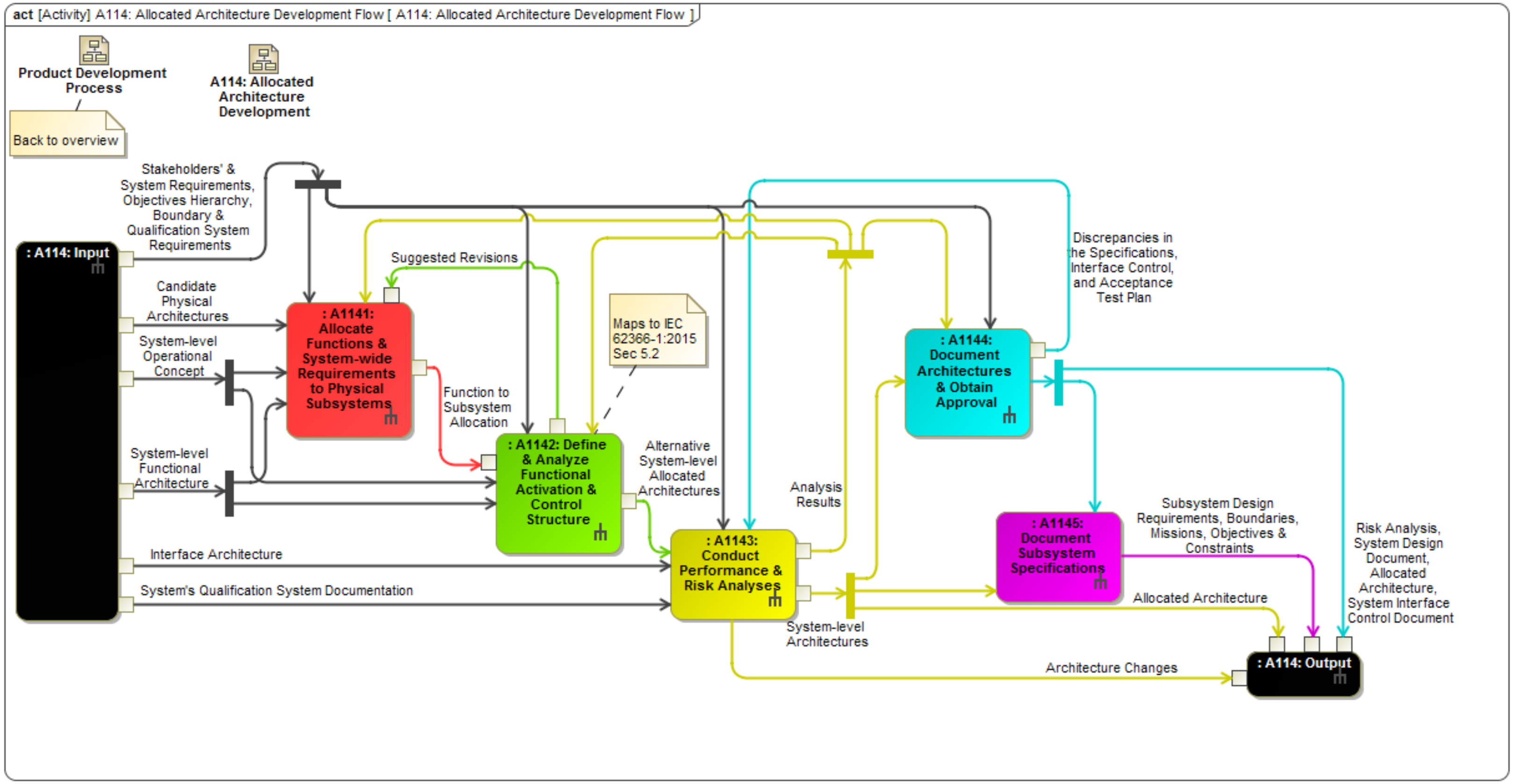

Figure A.12. Information Flow During Architecture Allocation

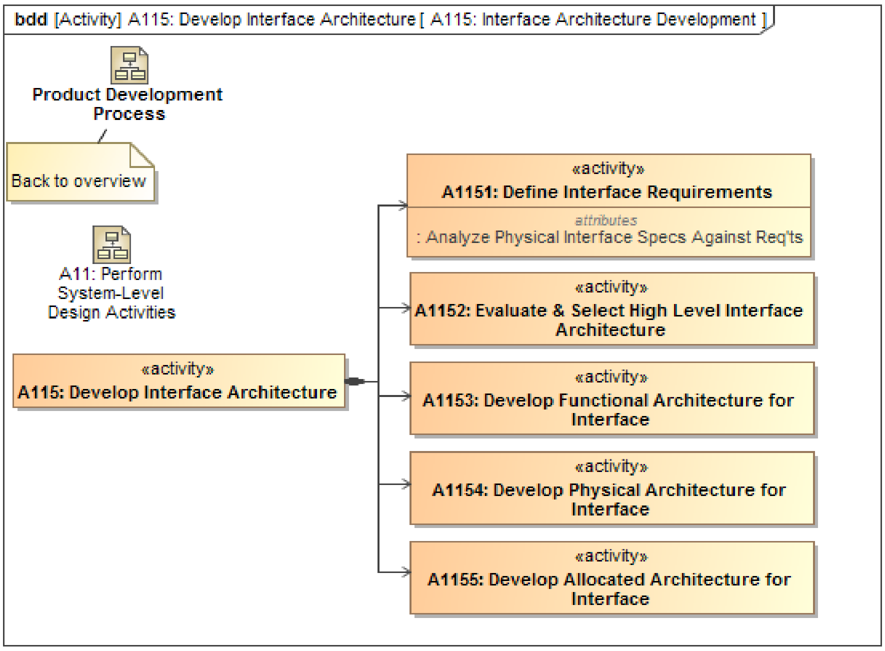

Figure A.13. Interface Architecture Development - Block Definition Diagram

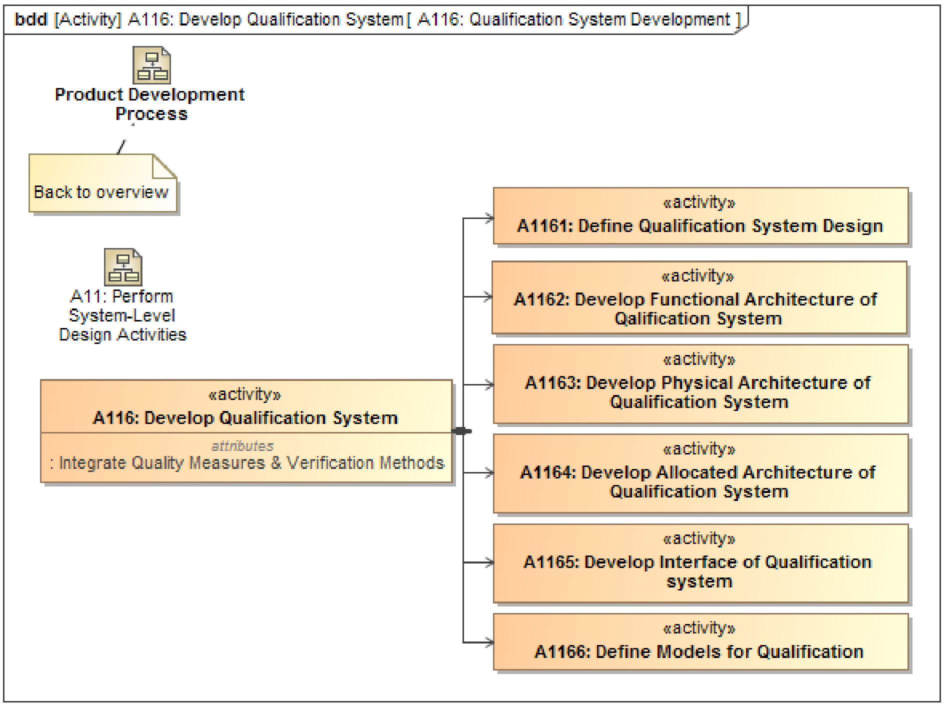

Figure A.14. Qualification System Development - Block Definition Diagram

Content Diagram Product Development Process [Mapping with ISO 14971]

Mapping ISO 14971 to Buede's Diagrams

14971	Buede's Diagrams		
Risk Analysis Step	**Produced by**	**Part of Artifact**	**Feeds to**
Intended Use	A1111 Develop Operational Concept	System-level Operational Concept	
Identify characteristics related to safety	A1111 Develop Operational Concept	Preliminary Hazard Identification	System-level Operational Concept (using FDA guidance document, etc.)
	A112 Develop System Functional Architecture	Functional Hazards *(from use cases)*	System-level Final Architecture
	A113 Design System Physical Architecture	Physical Hazards *(from use cases)*	Physical Architecture
	A1142 Define & Analyze Functional Activation & Control Structure	Emergent Hazards from Activation & Internal Structure	Alternative-level Allocated Architecture
Risk estimation	A1143 Conduct Performance & Risk Analyses	Estimated Risks	Analysis Results
Risk Control	A1143 Conduct Performance & Risk Analyses	Risk Controls, Option Analysis	Architecture Changes
Risk Management Report	A1144 Document Architectures and Obtain Approval	Risk Evaluation in Risk Management Report	Risk Analysis

Notes:

- **Stakeholder's constraints in A111 are the user constraints for the healthcare domain. (Think about the patient).**
- **Regulatory bodies' constraints mostly feature in the Qualification constraints from IEC 62366-1, ISO 14971, ISO 15288, etc.**

Figure A.15. Mapping process diagrams with ISO 14971

B. Traditional Top-Down Systems Engineering (TTDSE) and Platform-Based Design (PBD)

The *"Vee"* diagram is also referred to as the Traditional, Top-Down Systems Engineering (TTDSE) Approach where we start at the top with the high-level system definition and break it down until we reach the specifications of the CI which are designed by the discipline engineers. In this section, we contrast this top-down approach with another design methodology, platform-based design (PBD), which was proposed by Sangiovanni-Vincentelli [62].

PBD is defined as *"an integration oriented design approach emphasising systematic reuse, for developing complex products based upon platforms and compatible hardware and software virtual component, intended to reduce development risks, costs and time to market"* [63]. This approach has its roots in the semiconductor and electronic design automation industry but [62] argues that due to its abstract nature, it is applicable to different industries including automotive, communication, computing,

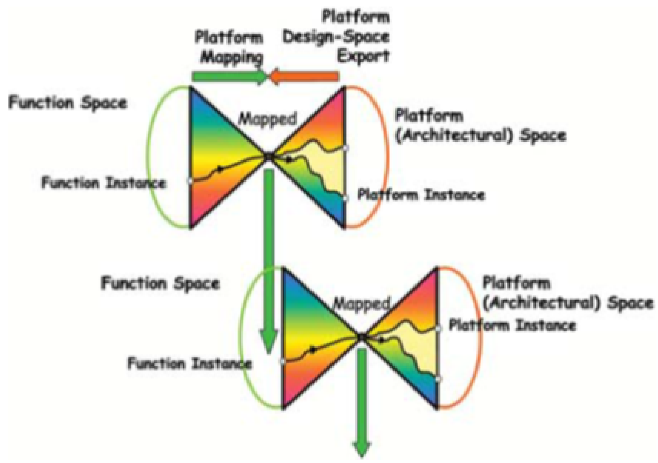

Figure B.1. PBD Process [62]

avionics, building automation, space, agriculture, health and security. The basic principle of PBD is to start the design process at the highest level of abstraction and break-down the implementation to a certain functionality level where it is mapped with a platform instance from the platform (or architectural) space. This mapping is then carried out at number of times at different levels of abstractions to go from the initial specification to the final implementation. The PBD process (as shown in Figure B.1) can be seen as a *meet-in-the-middle* process contrary to the traditional top-down (or bottom-up) approaches.

VITA

VITA

Apoorv Maheshwari is a Graduate Research Assistant in Purdue's School of Aeronautics and Astronautics and School of Industrial Engineering in West Lafayette, IN (US). He graduated from the Indian Institute of Technology, Mumbai (India) where he completed his Bachelors in Aerospace Engineering. He is currently a member of the Purdue System-of-Systems Laboratory and Product Lifecycle Management Center. His primary research interests are in the areas of applying model-based systems engineering to product lifecycle management, agent-based modeling, network theory, and the application of random-utility discrete-choice theory to air transportation system.