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ScienceDirect

Procedia Computer Science 44 (2015) 305 – 314

Procedia Computer Science

2015 Conference on Systems Engineering Research

Communication of simulation and modelling activities in early systems engineering

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Abstract

In this paper we present a framework that aids and supports communication of modeling and simulation activities in early systems engineering. We do this by analyzing existing simulation and modelling frameworks, both in systems engineering as well as more generic frameworks. For each framework, we discuss its purpose, main outcomes and the tools and methods used in the framework. Using this overview, we argue that in order to apply simulation and modeling techniques fully in conceptual systems design, it is necessary to use a framework focused on communication and aimed at four key issues. We extract a generic process from the discussed frameworks and discuss for each step of this process how these issues should be addressed. We also explain how this framework should be supported with tooling. Finally we discuss a simulation study of a medical imaging system that gave us initial experiences on the approach presented here. We conclude that this framework shows promise in supporting the communication of a modeling and simulation study in a multidisciplinary setting.

Peer-review under responsibility of the Stevens Institute of Technology.

Keywords: Modeling and simulation; multidisciplinary communication; communication support; conceptual systems engineering

1. Introduction

Modeling has always been a core activity of any (systems) engineer. Since the beginning of the "information age", more techniques arose and were made available to execute these models, resulting in simulations. The main goal of simulation activities in systems engineering (SE) is to investigate, verify and validate a system's behavior in relation to its context. The simulation model and its insights can then be used to do for example performance evaluation, evaluation of design alternatives, risk assessment and uncertainty reduction in decision making[1]. Many

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Peer-review under responsibility of the Stevens Institute of Technology.
doi:10.1016/j.procs.2015.03.021

tools and frameworks exist in this regard. However, we argue that adequate support and knowledge about how to effectively and efficiently transfer and communicate the findings in a multidisciplinary design team is still lacking. This is especially important in the conceptual stages of systems engineering. In previous work, we have stressed the need to share insight across multiple disciplines and discussed obstructions to do so[2]. Madni et al.[3] also underline our view[4] that there is a need for more accessibility than SysML and Object Process Methodology (OPM) offer to non-engineering stakeholders. Furthermore, we agree with Canedo and Richter[5] who state that it is key to have meaningful evaluations of design choices as early as possible. In this present work, we propose a method that focuses on communicating modeling and simulation activities in the conceptual stages of systems engineering.

This paper is organized as follows. In section 2, we review modeling and simulation in SE. In section 3, we outline the problem that our framework addresses. We propose and discuss our framework in section 4. Section 5 describes a case study which served as a basis for the framework proposal. In section 6 we discuss our results, conclude and outline future work.

2. State of the art

In this work, we consider various aspects of the state of the art. First of all, we analyze modeling and simulation in SE. Then, we look more closely at several key points in the early, conceptual stages of systems engineering. Finally, we discuss various options to support communication in a multidisciplinary design team, which gives us an idea of how we can share information that addresses existing information needs.

2.1. Modeling and simulation in SE

When discussing modeling and simulation, we use the following definitions[6]:

- A model is “a mathematical, logical, physical, or procedural representation of some real or ideal system”
- A simulation is “the implementation of a model in executable form or the execution of a model over time”.

According to the definition, a simulation does not necessarily have to take place in a computer tool, it simply is executing a model over time. A thought experiment can be called a simulation as well, as it considers a model in various instances. An example in this regard is using soft systems methodology via systemigrams[7].

As simulation and modeling have always been important concepts in SE, there is an extensive body of knowledge on how to support these techniques in a framework. In Table 1, we have analyzed several of these frameworks based on their purpose, the means with which they achieve this purpose, the main outcomes of using the framework and the tools, languages and methods used in the framework. We selected some more generic frameworks, several SE-specific frameworks as well as several newly proposed frameworks with a focus on the conceptual design stage.

Many of these frameworks focus solely on later design stages. For example Ryan et al.[8] even mention explicitly: “once the requirements are understood, the trade space is defined and potential architectures have been identified, simulation models can be designed”. Modeling and simulation are certainly paramount in this stage of the design. However, the conceptual design stage receives no support within this framework, while very critical and influential decisions are made in this phase. We would argue that one of the key parts of the conceptual design stage, understanding the problem, can be very well supported with simulation models. The main question here is how to communicate the insight gained effectively across multiple disciplines.

Canedo and Richter[5] state that determining the impact of new design alternatives is not supported well by state-of-the-art design tools. In addition to this, Yaroker et al.[9] state: “conceptual design is a crucial system lifecycle stage, but systematic methods for conceptual design evaluation are not well developed”. Unfortunately, these works do not address how to share the results of these analyses across a multidisciplinary design team.

2.2. Conceptual systems engineering

We can identify the key issues in the conceptual stages of systems engineering by looking at activities taking place in this phase. The INCOSE Handbook[10] separates the conceptual phase in a conceptual stage and an exploratory research stage, whereas Blanchard and Fabrycky[11] consider this one phase. From the descriptions of this phase in these references, we extracted two main points that play a central role in this stage of systems engineering.

Table 1 – Review of frameworks supporting modelling and simulation in systems engineering, those focusing on the concept stage are bolded

Framework Name (and reference)		**Purpose**
Means	**Main Outcomes**	**Tools & language**
Simulation Modeling and Analysis [Law 2014][12]		Avoid heuristic model building, programming and a single simulation
A generic simulation study process description with emphasis on validation and verification	*- Design and analysis support* *- Determining requirements*	*Written assumptions document* *No specific tools*
Modelling and Simulation: Exploring Dynamic System Behaviour [Birta & Arbez 2013] [1]		Developing a meaningful representation of the System Under Investigation
Activity-Based Conceptual Modelling	*- Leveraging of behavioral data* *- Capture of relevant details, avoid superfluous features*	*ABCmod conceptual model* *Three-Phase simulation model*
Systems Thinking: Coping with 21st Century Problems [Boardman & Sauser 2008][7]		Organize thoughts and actions relative to the system of interest
Framework for systems thinking, considering product, process and enterprise as a whole	*- Models reflect system and serve as discussion tool* *- Insight in relevance of different views*	*Systemigrams* *Soft Systems Methodology*
Architectural Design Space Exploration of Cyber-Physical Systems using the Functional Modeling Compiler [Canedo & Richter 2014][5]		**Evaluate the system-level impact of domain-specific design decisions**
Functional modeling to perform architectural DSE using multi-disciplinary simulations	*- Detailed multi-domain design space exploration*	*Functional Modeling Compiler (FMC)* *AMESIM / Modelica*
OPM Conceptual Model-Based Executable Simulation Environment [Yaroker et al. 2013][9]		**Find mismatches between design and requirements considering dynamic aspects**
Object Process Methodology Model-Based Simulation	*- Improved behavioral analysis* *- Degraded structural analysis*	*Object Process Diagram* *OPCAT*
Model-Driven Design-Space Exploration for Software-Intensive Embedded Systems [Basten et al. 2013][13]		**Systematic evaluation of design choices early in the development**
Intermediate representation allowing connection of tools and techniques	*- Integrate languages and tools in a unifying framework*	*DSE Intermediate Representation* *CPN / Uppaal / SDF3*
MBSE in Support of Complex Systems Development [Topper & Horner 2013][14]		**Understanding of critical components , interfaces and processes**
Conceptual modeling using a light weight, agile approach (ICONIX)	*- Facilitate communication & collaboration* *- Reuse components & results, improve traceability, information management*	*ICONIX* *UML / SysML*
NASA STD 7009 [NASA 2008][15]		Offer critical decision support
Standardize / Certify and document simulation procedure	*- Assurance that the credibility of models and simulations meet project requirements*	*COTS tools* *Delphi Method[16]*
MBSE to Improve Test and Evaluation [Bjorkman et al. 2013][17]		Systematically reducing uncertainty
Coupling of simulation and test results	*- Uncertainty predictions are easy to obtain and visualize*	*SysML/UML* *Monte Carlo*
Leveraging Variability Modeling Techniques for Architecture Trade Studies and Analysis [Ryan et al. 2014][8]		Representing sophisticated design options
Extending parameterized trade studies with variability modeling	*- Current configuration of design decision;* *- Increased communication* *- Traceability and potential for SE reuse*	*SySML* *Matlab* *Excel*
Executable system architecting using SysML in conjunction with CPN [Wang & Dagli, 2011][18]		Static and dynamic system analysis and formal verification
Conversion of SysML-based specifications into colored Petri nets	*- Visualize a proposed system* *- Analyze the problem domain* *- Specify architecture for solution domain.*	*SysML* *CPN (colored Petri nets)*
Key concepts in modeling product development processes [Browning et al. 2006][19]		Integrating the disparate models in use across an organization
Using activities and deliverables as key concepts in a generalized product development framework	*- Structure and reuse knowledge* *- Improving organizational, tool and product integration*	*PD process model*

Defining the problem through stakeholder needs

In the INCOSE Handbook, stakeholder needs play a key role in both the exploratory research stage (clearer understanding) and in the concept stage (aligning requirements with expectations). Blanchard and Fabrycky[11] mention this as "identifying problems and translating them into a definition of the need". The main issue here is to define the problem based on the stakeholder needs and validate this problem. This can be done using solutions, but care must be taken that the focus of the discussion is not on the solution, but on the problem. Korfiatis and al.[20] list several tools to elicit stakeholder needs in the conceptual stages of systems engineering. They mention several methods but indicate that interviews and focus groups are still most common. They propose to move away from these mostly paper driven methods and work towards a more shared mental model. Their work leverages a graphical and virtual CONOPS[20] (concept of operations) to allow stakeholders to express their needs.

Key influences on system behavior

The second main issue is to identify and characterize key influences on system behavior. According to the INCOSE Handbook[10], in the exploratory research phase it is important to assess whether technology is 'ready' to be implemented in a new system. This assessment is essentially ensuring what impacts these technologies or ideas have on the behavior of the system under design and its context, both functional and performance wise. In the conceptual stage the system behavior is detailed one step further and actual problems are identified for system elements. Blanchard and Fabrycky[11] mention similar issues, as they for example state that the conceptual phase should provide insight in "identifying and prioritizing technical performance measures and related criteria for design". Modeling and simulation help greatly in determining and showing key influences on system behavior[18].

2.3. Communication Support

"Communicating strategic intent cannot be entrusted to writings alone, nor to the presentations of the author. Additional support is needed—support that is faithful to the statements expressing the strategic intent, but value adding"[7]. This quote emphasizes the need for adequate communication support in SE. Multidisciplinary communication plays a key role[21] and is especially relevant during the conceptual stage. One of the authors has discussed communication in systems engineering in more depth in previous work[4]. In order to enable communication, it is helpful to have a common language or shared mental model of the system under design. Model based system engineering (MBSE) aims for this with for example SysML[8, 14]. However, as stated in the introduction, SysML is not accessible enough for non-engineering stakeholders[2, 3]. Another approach is the Design Framework[22]. This framework provides a mechanism to use heterogeneous models for different system elements and links them using design parameters. When considering communication support that includes non-engineering stakeholders, we have identified two main directions. This is either by using virtual reality and visualization[3, 20] or by condensing relevant architecting information into a single and accessible overview. This is for example done in the A3 Architecture Overview method[23].

3. Problem statement

As was shown in Table 1, various frameworks have been developed for modeling and simulation. Some of these frameworks mention the conceptual stage of systems engineering explicitly[5, 9, 13]. However, most of the frameworks are focused on later design stages. Birta & Arbez[1] state "it is never meaningful to undertake a study whose goal is simply 'to develop a model of ---". With this statement, they emphasize that a goal should be defined before starting the modeling and simulation activity. In conceptual design, communication with stakeholders and finding out what is the problem is key. This requires a different approach than when for example an optimal system configuration is sought in a trade study in more traditional simulation studies.

Boardman and Sauser[7] emphasize the following: "We believe that simulating the product (or service) has had a fair crack of the whip. It is time for visibility into the black box to convey confidence that what will emerge will be what people really need. We call this competence demonstration … as opposed to technology demonstration". The other frameworks in Table 1 make no explicit mentions towards this concept and while Boardman and Sauser offer systems thinking as a generic tool in this regard, there is no adequate implementation yet. Altogether, we feel this is necessary to adequately utilize simulations in conceptual systems engineering.

Table 2 – Important issues in conceptual systems engineering

Accommodate multidisciplinary views[2]	In the conceptual stage of systems engineering, a broad audience is involved. Where possible jargon should be avoided an multiple views should be supported to connect stakeholders more easily.
Support divergent design space exploration[2]	In the early stages of systems engineering the goal is not to optimize a system, but to explore and consider multiple options. In this stage, thinking out-of-the-box is very important. This in turn means that there should be a greater emphasis on the problem domain.
Dealing with uncertainty[2]	Uncertainty can come in various forms and shapes. This can be either uncertainty in a parameter, uncertainty in the systems functionality or even uncertainty in the systems context.
Lack of formality	Conceptual systems engineering and multidisciplinary communication is informal by nature. However, simulation usually requires a significant measure of formality.

In our review, the only framework that puts a lot emphasis of on several communicative aspects of a simulation study was what is considered the “Bible” on simulation[12]. One of these is maintaining a written assumptions documents, and another is to interact with the manager on a regular basis. However, no guidance is offered to which information is to be conveyed, or how one should select information or structure its presentation.

This lack of guidance is a problem because there are many issues that inhibit effective communication and an efficient simulation study. We identified in previous work[2] that especially in conceptual stages, three issues are relevant when performing a simulation study in early systems design. In this work, we extend this with a fourth issue. These issues are summarized in Table 2.

Concluding, due to the complex nature of systems engineering, simulations can play an important role in giving insight in a system’s behavior, even in the early conceptual stages. However, support is still lacking, especially when considering communication support in these type of activities. In order to address this, we propose a framework that guides modeling and simulation in the early stages of systems design. It is focused around the identified relevant themes and is especially focused on communication, to be able to utilize simulations as a means to show the impact of the system on all stakeholders, to all stakeholders.

4. Framework

In this section, we discuss our proposed framework. It deals with the four key issues mentioned in Table 2 and focuses on supporting communication. The framework consists of three pillars[24] that are essential for successful systems engineering. First, we will discuss the process that defines the way of working and structures the development. Then, we will discuss ways of thinking that can be used throughout the process. Finally, we will discuss the tool that can be used to execute and support this process.

4.1. Process

The process in this framework is based mainly on the work of Law[12] and our previous work[2]. It can be seen in Figure 1 on the left side. The process consists of six steps. The sixth step is the validation and communication of results.. This activity takes place the whole process, indicated by the fact that the block moves up on the right side next to the other blocks. The distinction between problem and solution domain is indicated by the blocks on the left. This means that step 1 & 6 are fully in the problem domain and 2 & 5 partly. The other steps are in the solution domain. The arrows indicate that the process is iterative and can return to any previous step when so desired.

4.2. Ways Of Thinking

Ways of thinking could be considered as lenses (or thinking tracks[24]) that can be used to view the system. In Figure 1, we indicated for the four issues outlined in Table 2, how they should be approached in every step of the modeling and simulation process. In this section, we elaborate on these issues and corresponding ways of thinking.

Multidisciplinary Communication

In the first step it is important to identify all relevant stakeholders, thinking about both the system's lifecycle and its operation, and to determine which views need to be represented. In the next few steps it is important to focus on validating the assumptions, as well as verifying the model's behavior and finally aim to validate the results[12]. Verification and validation of simulation results is described extensively by Sargent[25]. When presenting the results, this communication should be geared towards allowing stakeholders to not only think about the specific case presented, but also the more general implications. This presentation should include relevant views, the key influences on system behavior and an explanation on how they influence the system behavior.

Problem focused approach

When we start reasoning about the problem, it must be very clear to the stakeholders what the goal of the simulation study is[1]. In the conceptual stages, the goal should be to more clearly define the generic problem, and not to find an optimum solution for the specific problem at hand. When the solution domain is entered, it should be done with care and at first with an explorative mindset. Using functional descriptions and analysis is preferable, since they are solution independent[5]. So, the goal of a simulation model should be to support basic behaviors that aim towards broad understanding. When parameters are introduced, one should always be able to vary these, because this allows for what-if exploration. Then, when performing experiments, we are most interested in finding key concepts that determine the behavior of the system. This includes thinking about the system's dynamic characteristics and feedback loops. And once again, when presenting the results, present them in a way that leads discussion towards the problem and not towards the solution. For example, by avoiding to present a very specific system model, but to merely present and discuss the generic issues that dictate the system's behavior.

High uncertainty

Conducting a simulation study in the conceptual stages of SE means that there is an inherent high uncertainty. When defining the design problem, this will surface due to the fact that there is no architecture concept or it is still very vague. When defining the system model, it is thus key to also quantify the context of the system and consider possible risks. When constructing the simulation, generic behavior can be modelled for the system. If this is done flexibly, a great range of dynamic properties can be explored. In the resulting steps, it is important to think about the impact that various inputs from the system context have on the system's output and vice versa.

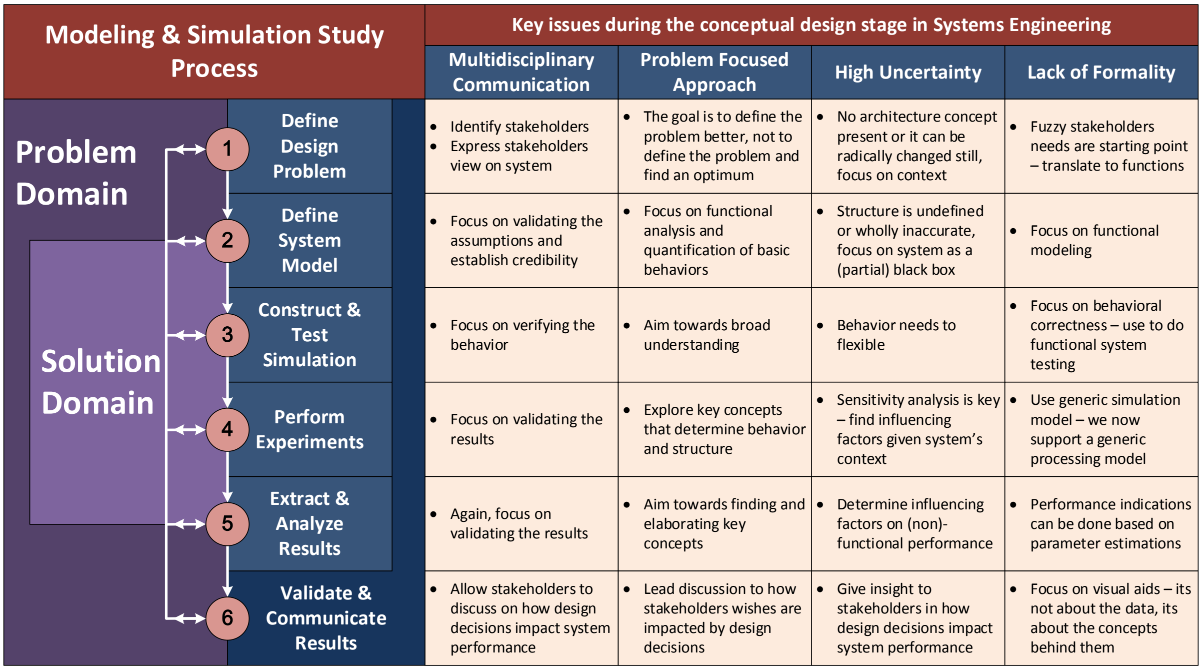

Figure 1 - Framework to guide modeling, simulation and communication in early stages of systems engineering

Lack of formality

We advocate a functional reasoning approach to deal with the lack of formality[5]. In this case, it is important to focus on functional modeling and on behavioral correctness and richness. When visualizing the model and simulation, the key question should be whether the behavior corresponds with the expectations of the stakeholders. By using a generic simulation model, like we already implemented[2], it is possible to simulate without the need of introducing too much detail or domain knowledge. Thinking about the various scales that system parameters can have supports constructing the system model for simulation. Finally when presenting, the focus should be on visual aids, and not on the technical implementation of the system itself. By using these visual aids, the communication becomes more domain independent and draws the discussion away from technical details that are not relevant.

4.3. Tools

In this section, we elaborate on the proposed tooling for the framework. Based on the fact that we envision a fairly informal process, we do not strive towards highly formalized tooling. In fact, there is an inherent opposition between understandability and formality[4]. A 3D-CAD program would not fit in this view for example, except maybe if it is only used for visualization.

Communication Medium

The most important tool of the framework is in our view the communication medium. We already indicated that the A3 Architecture Overview (A3AO)[23] has proven itself as a good multidisciplinary communication tool. In our case implementation, we used this paper based format for presentation the results of our simulation study. However, we could only give limited insight in scenarios and consequences of changing key concepts in the system due to space constraints. From this we concluded that the paper based A3 format does not offer the required interactivity to support a simulation study. In our group, more interactivity in A3AO's has been a recent subject of research[26, 27]. This provides us with the confidence that when we implement a digital form of the A3AO, it will allow us to leverage interactivity as well as retain the original and effective concept of the A3AO.

Process Support

The process support can be embodied in several different ways. It can be either free-flow or very rigorous. In the first case, a set of guidelines would be appropriate, in the latter case a format using templates could be envisioned. Also, all steps can be loosely described or documented more extensively. In our case we choose to follow a more free format, that is however supported with a wizard-like computer environment in which the various issues will be presented as guidelines in the various steps, leading to a stepwise, iteratively created digital A3AO.

Feedback Support

To support feedback various directions are possible. First of all, there are the more classical paper based reviews. On the other hand, workshops using tangible representations of the system[28] or virtual reality representations[3, 20] can be used as well. Another option is to use for example the Delphi Method[16] to assess credibility of simulations. The Delphi method is an iterative group decision technique. In our tooling, we propose to use the Delphi method in combination with more classical based reviews, and because the online environment allows it very well, more interactive, interim review and communication possibilities in a shared working environment[26, 27].

Modeling Language

As we already indicated our aim to use the A3AO approach and consider the simulation activity to be informal, it does not make sense to use a rigorous modeling language like SysML. Therefore we do not aim to use a specific modeling language, other than the functional modeling language used to represent the system. This could be OPM[9], but we rather use the Y-chart methodology[2, 13] in defining our systems as this allows a more generic simulation approach.

Simulation Tool

In our current case implementation we used SheSIM[29] as simulation tool. However, we have not specified this framework to be used with SheSIM per se. We do want to note that discrete-event simulations are more suited to simulate conceptual systems. This is because we are often more interested in the system as a whole than exploring physics based principles. Exclusively conducting thought experiments based on systems thinking is not advisable as well, though it can be a good starting point. If however some more constructive analysis is to be executed on the system model, formalizing this using a discrete event approach is most logical.

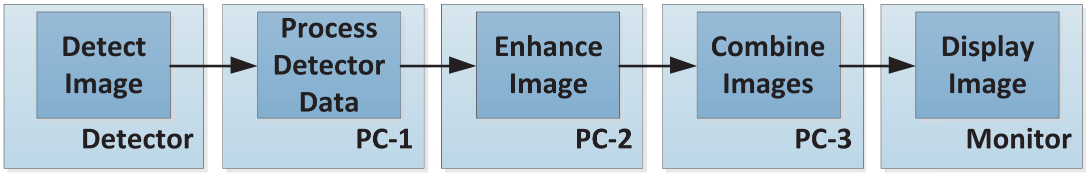

Figure 2 - System model of imaging chain. Smaller boxes are processes (functionalities), large boxes are resources

5. Case Study: initial implementation

This section will give some insight in how we worked towards the framework, proposed in Figure 1, in a case study. In the case study, we focused on determining how to communicate simulation results effectively and efficiently, however, we will discuss the case study following the process structure we proposed in the framework. Our case study concerned the analysis of the image processing chain of a medical imaging system .

Design Problem Definition

In a medical imaging system, the imaging chain determines several key aspects of the system. Next to leveraging high quality images, especially in interventional imaging systems as in our case, timing is very important. In previous work[2] we already started this analysis. In that work we focused on the latency of the imaging chain, as this ideally cannot be higher than 165ms to ensure proper hand-eye coordination for a physician performing an interventional procedure. However, not only the latency time has influence on the hand-eye coordination. The variation in latency times, also called jitter, is noticed by physicians when a certain threshold is exceeded, which degrades the user experience. If physicians detect jitter, which is not desirable of course, we call this a glitch.

The goal of this simulation study was very generic, as is advocated in the framework. The goal was to provide awareness and guidance on which elements of the imaging chain determine this jitter behavior.

System Model Definition

We defined the system model following the Y-chart paradigm[30]. The system model can be seen in Figure 2. Here we can see that an image is first detected, then the detector data is processed. After that the image is enhanced. Then the image data is combined with images from other sources and finally displayed. As stated in the framework, this system model is very basic, but we experienced that this abstracted system model already offers enough insight in the stated problem when combined with the behaviors that were implemented in the simulation model.

Construct & Test Simulation

To construct the simulation, we mainly analyzed which behaviors were to be included in the system. As we were looking at jitter, we included various sources of variance that were present in the system. We used mainly interviews with engineers active in various parts of the imaging chain to determine this. We also immediately verified the outputs we already had achieved in these interviews to validate the simulation.

Perform Experiments

After we were satisfied with the initial results of the simulation, we performed experiments. In this case this was mainly a sensitivity analysis of the simulation results to determine how often certain phenomena occurred.

Extract & Analyze Results

In this phase, we used the data from the experiments to discover statistical significance and trends in the data.

Validate & Communicate Results

Initially we used a standard report format to document and communicate our results. However, as we were speaking with specialists from different domains (also image quality and user experience specialists) we started to combine different views throughout the report, and made a lot of supportive drawings to explain certain concepts (visual aids). We did not experience this way of reporting as optimal and as mentioned before, we changed the communication format to an A3AO[23], actually also prompting the research presented in this paper. While we managed to create an overview of all relevant aspects of the simulation study, we had to sacrifice readability to combine everything on one A3. The resulting A3AO is not included in this paper due to confidentiality reasons. However, its structure can be seen in Figure 3.

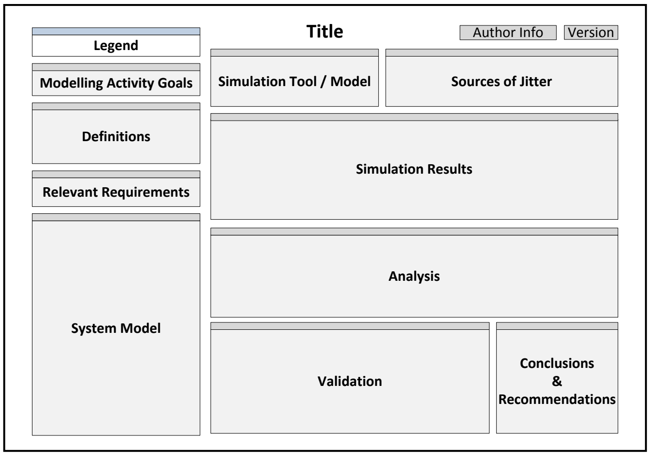

Figure 3 - Structure of the A3AO used to communicate the simulation study results, visual aids were used throughout the A3AO

6. Discussion

We experienced that the way we approached the problem and communicated the results helped in driving the discussion with stakeholders to the broader concept of how to deal with jitter in general, than focusing on a specific configuration of the system that was relevant at that time. Furthermore, in our initial experiences, when using the A3AO overview in communication, stakeholders were able to get a better overview of what was done in the simulation study and how various steps in the process related to one another. However, stakeholders also had more in depth questions towards certain statements and several what-if questions regarding a change in certain system parameters. The paper based A3AO that we used in the case study ended up too full, did not offer enough interactivity to explain enough scenarios, nor allowed to add additional information in a layer behind the original statement, for example as a pop-up window. This is why we move to a digital A3AO in the proposed framework to alleviate these problems. In this case study we have concluded that the A3AO overview is very useful in communication of simulation study results, mainly by getting overview and creating awareness of the problem at hand, but it lacks in interactive options that are necessary when communicating simulation study results.

Considering the review of the state of the art, we feel that it is very important to have a framework for simulation studies that emphasizes and is directly aimed at communication. This is, as identified, especially useful in the conceptual stages of systems engineering where multidisciplinary communication is key, but can also be important for simulation studies in general. Another interesting topic for discussion is whether to integrate such a simulation study into an overall MBSE framework and in what manner. Bjorkman et al.[17] already showed that it can be valuable to couple testing procedures to simulation studies, to gain mutual benefits. The Design Framework[22] advocates that it is important to capture design rationale throughout the various lifecycle phases. Using a more rigid MBSE framework, based on for example SysML would allow the results to be more automatically connected to other parts of the development process, but we feel that the loose coupling of the A3AO is actually one of its strengths and we seek to preserve that, which is why we do not aim for integration in this current state.

Future Work

In future work we aim to implement the proposed framework and test this framework with various stakeholders. Also, we aim to do this in more domains than the medical imaging domain. The simulation model that was currently developed is able to generically simulate other processing applications as well. However, we also look towards other applications. In upcoming work we will focus on leveraging a computer tool that supports the process proposed here, pays special attention to the issues mentioned and leverages the same type of overview an A3AO does, but with more interactivity.

Acknowledgements

This publication was supported by the Dutch national program COMMIT, as part of the Allegio Project. We would like to thank our lead partner, Embedded Systems Innovation by TNO, and other partners, for their support. Finally, we would also like to thank the reviewers for their insightful feedback.

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