A conceptual model to support communication of systems modeling and simulation activities

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***Abstract*— Modeling and simulation studies can greatly increase insight in the behavior of complex systems. However, if the person executing the study is unable to communicate its results, the usefulness of the effort is significantly reduced. The multidisciplinary nature of systems engineering and architecting impedes an easy transfer of knowledge in this regard. In this paper, we discuss simulation activities from a communication viewpoint and describe the key elements in this process. These elements are brought together in a conceptual model. We then discuss how this model can be utilized using the principles of the A3 Architecting Overview method to enable more effective and efficient communication of modeling activities. Finally we show an application of this approach and discuss its results and impacts. We conclude that while the conceptual model is complete for the presented application, more research in other domains is necessary to fully validate the model.**

Keywords—systems engineering; modeling and simulation; multidisciplinary communication

I. INTRODUCTION

To properly design a complex system, a system engineer must understand its behavior under various circumstances. Various techniques can support a system engineer in this process, for example modeling and simulation. Unfortunately, this is only one piece of the puzzle. Because, if a system engineer, or any other stakeholder involved, is unable to communicate the insight gained, this knowledge cannot be utilized properly to design the system. It is therefore paramount to enable and ensure communication of those system characteristics that impact its performance and functioning. This is especially true in the early stages of systems engineering, where the system is still undefined and multiple disciplines, also non-technical ones, are closely involved [1].

In this work, we discuss the core concepts in systems engineering (SE) that give a foundation for and enable multidisciplinary communication. We then describe how to communicate modeling and simulation activities in early SE using these concepts based on the A3AO (A3 Architecture Overview) method [2]. An example case study is used to illustrate how to apply this in a practical manner.

This paper is structured as follows. In section II, we discuss the background of our research. In section III, we introduce the core concepts required to communicate modeling and simulation activities in a multidisciplinary environment. In section IV we discuss which concepts are currently represented in the A3AO method and how it can be extended to support all concepts. In section V, we give a practical example using a medical imaging case study. Finally, section VI discusses the usefulness of this approach and outlines future work.

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II. COMMUNICATION CHALLENGES IN SYSTEMS ENGINEERING

In this section, we explore several key challenges that relate to communication in systems engineering We do not focus on general communication theories, which have been discussed in a SE perspective in [3]. As we already stated in the introduction, communication is a key activity in systems engineering [4] especially in its early stages [1].

When we consider the current challenges in SE, communication is a central theme in many of them. For example, Torry-Smith et al. [5] pose nineteen engineering challenges. Of those nineteen, at least ten deal directly with communication. These can be seen in table I.

For three of the challenges listed in table I, we will offer a more detailed explanation of how the state of the art currently addresses these challenges and pay special attention to how they are represented in the earlier stages of systems engineering.

TABLE I. CHALLENGES RELATING TO MULTI-DISCIPLINARY COMMUNICATION, SELECTED FROM [5]

Lack of a common understanding of the overal system design
Lack of a common language to represent a concept
Transfer of models and information between domains
Different traditions within domains for how to conduct creative sessions
Reluctant to interact with engineers from other disciplines
Different mental models of the system, task and design related phenomena
Lack of common language to discuss freely at creative meetings
Education within disciplines do not call for integration in professional life
Knowledge transfer between domains is inadequate
System engineers are lacking detailed information of the system

- Common understanding of overall system design

Stakeholders from various domains each have their own models and approaches to describe and understand a system. However, approaches like functional modeling [6] can be used to describe the system at an abstract level. Especially in the early stages, this abstract level allows stakeholders from all domains to reason about the system appropriately. Another option is to use a more informal description, as is for example used in the A3 architecture overviews [2]. The combination of multiple views and support of visual aids allow all stakeholders to understand the system.

- Transfer of models and information between domains

Opposed to providing one accessible view to all stakeholders, model transformations aim to connect viewpoints by transforming one viewpoint into another. Sometimes an intermediate representation is used, such as SysML in [7]. Another option, is multi-domain simulation such as Modelica [8] or the bond-graph based 20-sim [9]. This works quite well, but has the drawback that is very heavily focused on the physical domains, which are often less relevant in early stages of systems engineering. It could however be used to also perform high-level synthesis, as is described in [10]

- Lack of common language to support creative meetings

The last challenge we discuss is that it is very hard for a group of stakeholders to reason together about a system, as there is a lack of a common language. SysML has been proposed as this common language but is less accessible for non-engineering stakeholders [11]. In [12] a more practical approach is suggested. Co-location of key stakeholders could influence collaboration and communication positively.

In general, Torry-Smith et al. conclude in [5] that while a common methodology and a common conceptual model are needed, this does not seem to be feasible as different views are always needed to describe a system.

III. Core concepts in communication, modeling and simulation

In this section we classify the core concepts that are relevant for communication of modeling and simulation activities in multidisciplinary systems engineering. To place

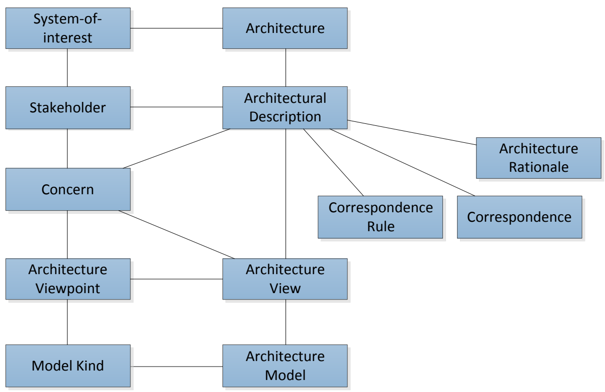

Fig. 1. ISO/IEC/IEEE 42010 conceptual model of an architecture description [6], relationship qualifiers have been omitted for readability

these concepts in a context, we connect them to the conceptual model of an architecture description as presented in the ISO/IEC/IEEE 42010 standard [13], see also Fig. 1.

To introduce the core concepts of communication modeling and simulation activities, we address several topics. The first is the development process in which the modeling and simulation study is conducted. The second is the simulation study process itself. The third is the relevant viewpoints and corresponding views that are central in this type of activity. Finally, we present a unified view on the discussed concepts.

A. Development Process

Various **design methods** can be employed to develop complex systems. These can either be more paper driven or model driven. When considering the position of **modeling and simulation studies** in these processes, they can be either considered loose entities or more tightly coupled to the design method, for example by integrating simulation and models with test and evaluation activities [14]. The study will also be executed at a certain **abstraction level**. As we are mainly concerned with the conceptual stages of systems engineering, we deal with high levels of abstraction. Within one abstraction level, we can iterate the simulation study, meaning that we stay at the same abstraction level. Executing the same study at a lower level would be considered recurrence [15].

B. Modeling and simulation study

While the development process gives the context for the simulation study, the study itself is a process as well. In [16], we describe a modelling and simulation framework for the conceptual design stages. The process in this framework has been adapted from the process described by Law [17], and consists of six steps. For each of these steps, we discuss the core concepts that relate to the conceptual model shown in Fig.1. Note that the process is considered to be iterative and separate steps do not necessarily have to be sequential.

1) Problem Definition

Due to the abstract nature of conceptual systems design, the **context (**or environment) of the **system-of-interest** should receive significant attention. By analyzing the context of the system-of-interest, the **stakeholders** can be identified. Then, in turn, stakeholder **needs** can be identified. The stakeholder needs will give reasoning for both the **concerns** and the **problem** definition. These could have the form of initial requirements or functions to be fulfilled. As simulations are the main tool to give insight in dynamic behavior of the system, the problem should have some inherent **dynamicity** [18]. Note that if the problem does not concern this dynamic complexity, simulations add little value. Finally, the problem definition can further lead to the definition of one or more study goals, related to the concerns. As simulation studies are more commonly employed in further development stages of system engineering [1], their goal traditionally is to optimize the system. However, in conceptual systems engineering the goal is often to define the problem better, instead of finding an optimum.

2) System Model Definition

To establish an **architecture** it is key to reason from several **architecture viewpoints**. We will discuss the relevant a**rchitecture views** in a separate section. The views are described with **architecture models**. The various views together form the **architecture description**. Combining various views with a **mapping** leads to the definition of a **system model**. There does not need to be one system model that fits the architecture description exactly. By varying the mapping, many system models can be created. The process of generating these mappings we consider to be creative synthesis [19] or design space exploration. Because we are reasoning at an abstract level, the design space exploration does not aim for an optimal solution, but rather aims to explore various ways to approach the problem.

3) Simulation Model Definition

In [20], simulations are defined as the "the implementation of a model in executable form or the execution of a model over time". This means that a **simulation model** can be established by extending a system model with at least an executable **formalism** to the model, and/or a **time** concept. Both approaches aim to quantify and qualify the **system behavior** and gain insight in its dynamicity. The formalism for a specific model is captured in a **model kind**. This model kind often concerns a specific **domain.**

4) Perform Experiments

The simulation model should already be created with the experiments in mind. So that when the simulation model has been created and validated, it can be used to perform these experiments. The experiments aim to uncover the **key system characteristics** that influence the systems behavior. For example a sensitivity analysis can be helpful in this regard.

5) Analyze Results

The key activity in this step is to contextualize, **visualize** and explain how the key system characteristics and the system behavior relates to the various system concerns that were identified earlier in the simulation study.

6) Validate & Communicate Results

Verification and **validation** [21] of results should happen throughout the simulation study. For example the system model should already be verified and validated after a first concept has been defined. This helps to ultimately represent the views of all stakeholders in the system model. Early validation also strengthens acceptance of the model and its outcomes in the later stages of the study [17]. During the development of the system model, various views have been constructed using architecture models with their own formalisms. This means that each stakeholder, on its own, or as a **group** has access to those models of which the formalisms are understood by that group or individual [22]. Ultimately, the goal is to give each stakeholder access to relevant information by offering them this particular information in **accessible views**. This then leads to a system engineer being able to come to informed **design decisions** together with the stakeholders, as all have the required insight to reason about a particular decision. This means that all stakeholders have access to the **architecture rationale**, as they understand the various relations, or **correspondences**, that exist between system elements and how these relations impact the system's behavior. The correspondences are governed by **correspondence rules**.

C. Essential views in modeling and simulation studies

To determine the essential and important views in modeling and simulation studies we have to consider the paradigm that we use for simulations. In recent work [1], we have found the Y-chart paradigm [23] very useful to simulate in the conceptual stages of systems engineering. The Y-chart methodology uses an application view and a platform view and combines those with a mapping. However, before simulation is possible, both of the views need to be quantified as well. This is akin to the tripod of a **functional view**, a **physical view** and a **quantification view** as recommended in [3]. Also, in [19] a functional view and structural (physical) view are key, as well as a description of use cases. However, there is no explicit mention of a quantification view. DoDAF [24] specifies a fairly large number of possible viewpoints. Views that return in the simulation study are the all viewpoint (the AV-1 product as problem definition), the operational viewpoint (OV-1, CONOPS diagram) and the systems viewpoint (SV-4 Systems Functionality Description). The operational viewpoint in DoDAF and in [19] (through use cases) provides the possibility to explore various scenarios in which the system can operate. This helps greatly in assessing risks and uncertainty for the system. Therefore, we feel that an **operational view** is also essential in modeling and simulation studies. The operational view helps to specify uncertainty due to changes in the environment and helps to consider a time aspect for the system. However, there is also internal uncertainty in the system, for example what the eventual value of a parameter will be. These kinds of uncertainty are better represented in in for example the quantification view and could be represented as suggested in [25].

Other viewpoints can be relevant as well on a case by case basis. This depends on the concerns that the stakeholders have. However, the four viewpoints presented here are essential in every simulation study. Especially because the presence of the tripod (functional, physical, quantification) support multidisciplinary communication very well [3], while the operational viewpoint supports communication of the system by introducing different contexts for the system to operate in.

D. Conceptual model

We have compiled the concepts that were mentioned in the previous sections in an overview. This overview extends the conceptual model of ISO/IEC/IEEE 42010 with the relevant modeling, simulation and communication concepts that were discussed. The overview can be seen in Fig. 2.

IV. Applying the Conceptual Model

In this section, we discuss how the concepts in the conceptual model can be applied to support communication. The basis we use to support communication is the A3AO method [2]. The A3AO method was developed to consolidate and communicate system architecture information. Architecting information for a specific concern is abstracted on two sides of an A3 paper, one side being a textual summary and the other side showing a structured model. Due to its informal nature, the A3AO gives access to architecture rationale for all stakeholders. Even though the A3 was not

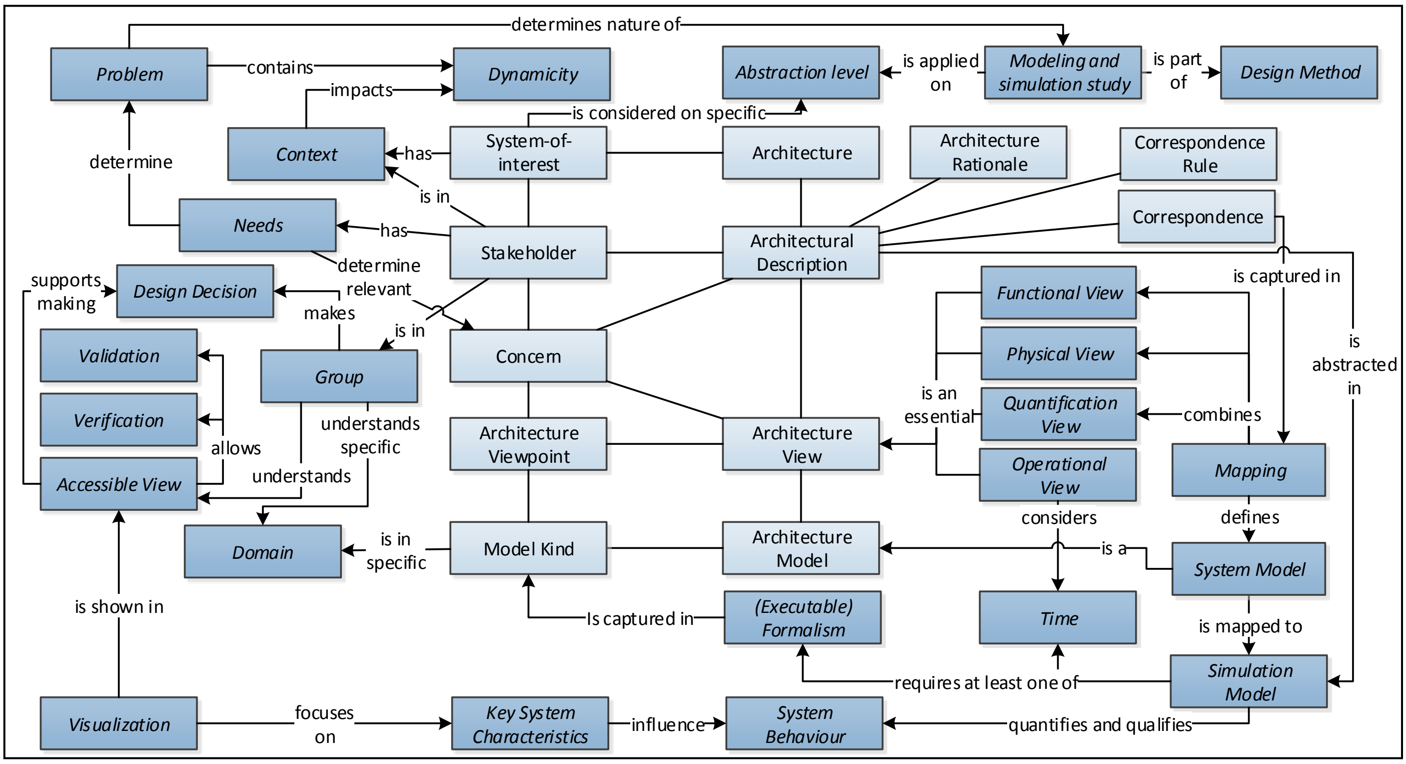

Fig. 2. Conceptual model of ISO/IEC/IEEE 42010 extended with communication and simulation concepts

designed for the communication of modeling and simulation activities, many of the concepts presented in Fig. 2 are already present in the A3AO.

The model side prescribes the use of a functional view, a physical view and a quantification view. It furthermore contains visualizations (visual aids) to support explanation of system concepts. Finally, the model side lists a number of design decisions and constraints and shows the reasoning or origin of these decisions in the various other views on the model side by linking them with icons. The textual side contains a problem and background description, a description of the stakeholders and their concerns, additional design rationale, a system view, a quantification of key parameters and requirements, references and links to other information.

Of the four views that were deemed essential, only the operational view is not represented in the A3AO method. However, Muller [26] created a subsea A3 architecture overview showing various workflows. This is done in a "comic book" style, meaning that various subsequent images show the system's state over time. In [27], a dynamic A3 architecture is used which allows various use cases of a lube oil system to be viewed. It is a digital implementation which starts in an overview with hyperlinks to more detailed A3's showing use cases such as "start-up", "running" and "shutdown". These two works give a good indication of how an operational view can be employed in an A3, either in the classical paper format [26] or digitally, in [27]. However, it can also be imagined that more interactivity is required. For example to allow the user to define operational scenarios themselves and directly see the resulting system behavior. In [28], virtual reality is used to enable stakeholders to create operational scenarios.

Next to an operational view, it is also necessary to support various mappings of the functional view on to the physical view, as in the Y-chart methodology [23]. This could be done by simply combining them in one representation, or linking the models that show the functional view and physical view. Because many different mappings can be relevant for the system's behavior, there needs to be a means to show these mappings, and to analyze their impact on the behavior. However, presenting all this information at once is bound to be overwhelming, so a good encapsulation strategy is necessary. Here, once more, digital support can be a solution.

Two important concepts that were described are verification and validation. In the A3AO method, this is not a concept that is mentioned explicitly. As the creation process of the A3 has a collaborative and iterative nature, this leads to intrinsic verification and validation of the A3. However, with simulations there is an inherent risk that it is unclear to stakeholders how the outcomes have been achieved, as the system's operation can and might even be a black box to them. It is therefore important to pay extra attention to explaining the key system characteristics that influence the outcomes and show how they were represented in the system model. This is the key to explaining the dynamic complexity that the system inhibits and also helps verification and validation immensely. This explanation should also quantify the uncertainty related to the key system characteristics, for example as in [25]. A final possibility is to use digital tooling to allow more ad-hoc based and faster review possibilities [29]. Which in turn can help to increase the stakeholders confidence in the simulation and understanding of the system.

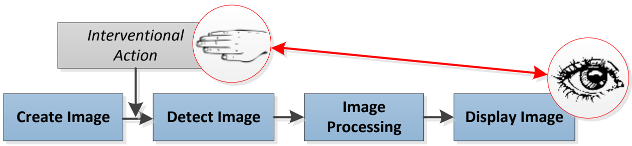

Fig. 3. Top level functional model of the interventional imaging chain

V. Examples from a Case Study

In the previous section we discussed how the conceptual model can be applied. In this section, we discuss several specific model representations to illustrate the application. In this paper we do not discuss the full version of the A3AO used to communicate. However, it can be found on the website of the first author via: http://tinyurl.com/jitterA3.

Our case study concerned a medical imaging system and focuses on the imaging chain of this system. Fig. 3 shows a top level functional model of the imaging chain and shows the main concern at the same time. As the medical imaging system in our case is used for interventional procedures, hand-eye coordination is very important for a physician. Hand-eye coordination is determined by two factors, the latency of the imaging chain and visible glitches (noticeable jitter) in the imaging chain. This problem definition can for example be visualized in a systemigram [30], see Fig. 4.

In the case study, we used a top-down modeling approach to focus on general behavior and to avoid discussion over details. For software engineers, it was for example commonplace to ask how context switches in the memory of a PC might affect the jitter at a certain moment in time. However, we used abstract concepts to model this kind of behavior and simply assumed that for example a PC had some kind of variation in the execution time. This allowed us to model the same behavior while avoiding a never ending sequence of detailing the system model. The eventual system

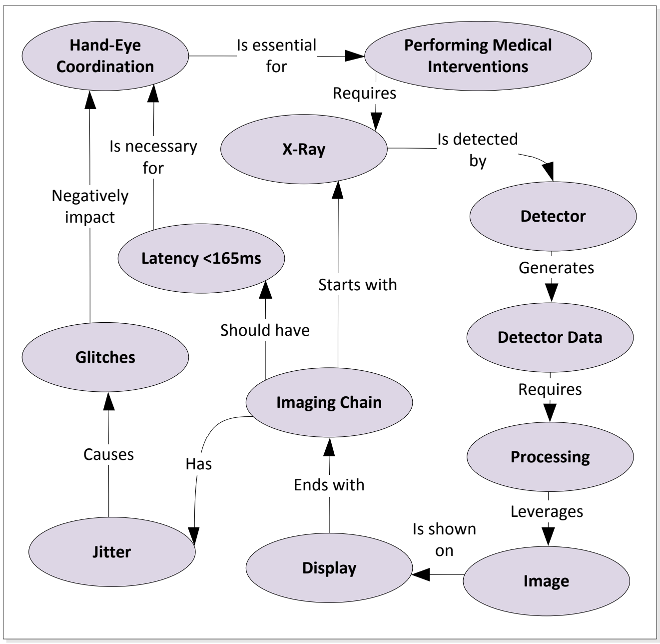

Fig. 4. Problem defintion expressed in a systemigram

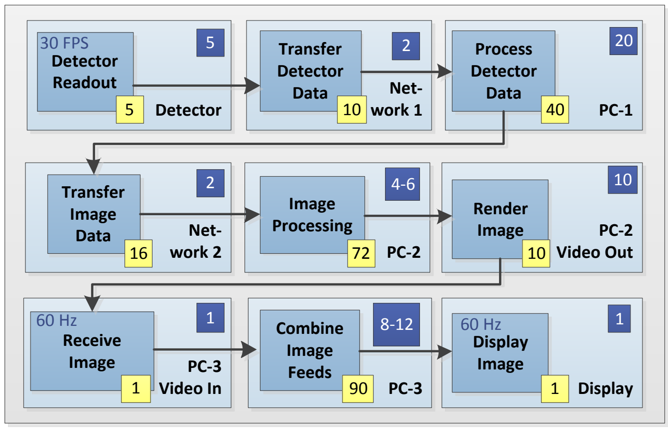

Fig. 5. System model, composed of information from functional, physical and quantification viewpoint. Functional elements (dark blue) are mapped to physical elements (light blue). The squares denote taskload for the functional elements and operation speed for physical components (both are unitless). The "30 FPS"' and "60Hz" indicate that those processes have a clock. PC-2 and PC-3 do not have a constant operation speed, but have an uniform distribution between the given numbers.

model and mapping that were the basis of our simulation can be seen in Fig. 5. We presented a similar version in [1] alongside an explanation of the simulation tool support. In this system model, information from different viewpoints has been combined into one model representation. This way, a mapping can be represented. However, many different mappings can be envisioned, for example by combining the functions executed on PC-1 and PC-2 on PC-2. This would remove PC-1 as well as a network 2 from the system model. The system engineer (assuming this person creates the A3AO) can either choose to show one specific mapping, show several different mappings, or allow other users to generate mappings themselves.

In the analysis of our simulation results we found that there are three influencing factors that cause glitches in the imaging chain. These are variance in execution times, phase alignment of clocks and processing exceptions (hanging PC). We communicated this as follows. First of all, in the A3AO, we indicated the three major sources of jitter and supported them with several visualizations to verify the presence of the sources to the stakeholders. Next, we outlined various simulation results in which we varied and combined these sources to show their impact on the systems behavior. To present this, we used the "comic book" style of [26]. This was both part of the sensitivity analysis while performing experiments, but also served as explanation for the stakeholders in the final communication. In this sensitivity analysis we found that sometimes a simulation run generated an excessive amount of jitter. We further analyzed this and found the cause of this issue. We explained this using visual aids, an example can be seen in Fig.6.

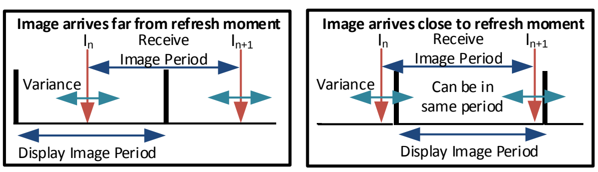

Fig. 6. Visual aid used to explain why glitches occur. Depending on the arrival time and variance of an image, two images can arrive in the same period. This means that one image is not shown, resulting in a glitch.

VI. Discussion

In this paper, we outlined the concepts that are relevant for communication of simulation and modeling activities in systems engineering. These concepts are based on the A3AO method [2] and were presented in a conceptual model using and extending the conceptual model of the ISO/IEC/IEEE 42010 [13]. After this we explained how to apply the presented concepts, both in general as well as with practical examples using a medical imaging case study. We presented these general concepts and refrained from prescribing an exact format. For example, in the case of communicating and constructing an operational view, it is useless to specify upfront that a general system model and a table with outcomes for various configurations is the optimal way of communication. It could also be an interactive configurator, showing users a single outcome every time the system model is adjusted. The specific realization could, and should, be different depending on the set of involved stakeholders, the goal of the simulation study and the industrial domain of the system.

Finally, the conceptual model that was presented does not claim to be complete, however it was currently sufficient to represent the concepts that were relevant in this particular case study. Future work will include conducting case studies in more industries to further validate the presented conceptual model, and to give more examples in its practical application.

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