INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.263

Utilization of the system architecture in the context of validation in the business-to-business (B2B) sector

Lynn Humpert [1,✉], Daria Wilke [1], Sarah Brueggemann [2], Harald Anacker [1] and Roman Dumitrescu [1]

[1] Fraunhofer IEM, Germany, [2] HARTING Applied Technologies, Germany

✉ lynn.humpert@iem.fraunhofer.de

Abstract

The European Green Deal aims to reduce global emissions by minimizing the use of resources. Early validation of products helps to reduce rework, costs and therefore resources. However, validation of complex mechatronic products is challenging due to interdependencies. Companies are applying systems engineering to meet this challenge. Current validation approaches are insufficient in the early design phases. This paper presents an approach to validation using the system architecture in the B2B sector. A machine tool and a custom built machine are presented as evaluation examples.

Keywords: validation, systems engineering (SE), system architecture, B2B sector, design methods

1. Introduction

The European Green Deal is a key step in realizing the European Commission's sustainability ambitions, with a central goal of curbing resource consumption to reduce global emissions (Europäische Kommission, 2023; Verein Deutscher Ingenieure, 2023).
This creates new challenges for today's companies. The pressure on companies to meet emissions targets and conserve resources is high. There is great potential in the early stages of product development in particular. This is where many mistakes (60% - 70%) are made and resources are consumed (Fischer, 2012). Undetected errors become more expensive as the development process progresses. For example, the design of a special machine may have to be fundamentally changed if the customer's production hall changes during the development phase. Such a continuation of mistakes must be avoided. Therefore, one way to save resources is to validate systems early on. Validation in this context ensures that the right product is being developed. To identify these changes in requirements early on, it is essential to involve relevant stakeholders, such as the customer (Verein Deutscher Ingenieure, 2021).
The issue of validation is well known, but it is particularly important in the context of sustainability. Early defect detection avoids late, resource-intensive rework since 85 percent of manufacturing costs are determined in the early phases (Verein Deutscher Ingenieure, 2018).
At the same time, product complexity is increasing. To manage this complexity, companies are increasingly utilizing systems engineering (SE) to work in an interdisciplinary way (INCOSE, 2023). SE can be of particular benefit, for example in the early identification of risks, in the management of customer requirements, and in internal communication (Wilke *et al.*, 2023). Linking SE with validation therefore holds great promise for further resource savings and increased digital continuity (Humpert *et al.*, 2023c). However, this requires new approaches and methods. Hence, this paper presents an approach of validation with the help of SE characteristics, especially the system architecture and the stakeholders in the system design phase.

The system architecture is the basic design and structuring of a technical system (Verein Deutscher Ingenieure, 2021). This can be used to help achieve the goal of conserving resources.
A machine tool and a custom built machine are used as examples of a complex system to evaluate the approach. The aim is to create an approach that uses the system architecture to identify changes in customer requirements at an early stage of development, thereby saving resources and avoiding errors at later stages. The Design Research Methodology (Blessing and Chakrabarti, 2009) was used to complete this research. The research question is clarified in the problem analysis in chapter two. Chapter three provides a more detailed state of the art of the first descriptive study. For example, a systematic literature review is presented. Chapter four contains the actual approach. This is the prescriptive study with the explanation of the developed approach. Chapter five describes the second descriptive study. The approach is applied to two examples. Finally, after a discussion, a conclusion is given.

2. Problem analysis

Climate protection and the associated reduction of emissions are being pursued at several political levels. At the global level, the Paris Climate Agreement has been adopted and the EU aims to become climate neutral by 2050 (European Commission, 2018). As part of this, the Green Deal Industrial Plan will accelerate Europe's transition to carbon neutral industry while maintaining competitiveness (European Commission, 2023). The opportunities for companies to exert influence are naturally greatest within their own company in the areas of product development, production and other corporate divisions, followed by direct interaction with customers (Verein Deutscher Ingenieure, 2023).
To avoid errors and conserve resources in the late stages of development, it is useful to specify the product or service in detail in the earlier stages of development. This is also shown by the rule of ten, which states that error correction across the life cycle becomes exponentially more expensive with every step in development (INCOSE, 2015). As described at the beginning, the error rate of 60 to 70 percent in the development phase of the system design shows the possible influence of validation on resource efficiency. Early validation thus can help conserve resources, and is essential for requirements management development (Humpert *et al.*, 2022).
This is why validation in this phase is so important and must be considered in the context of sustainability. While developing with prototypes in close collaboration with stakeholders to respond to changing requirements is an advantage, building prototypes is expensive and requires many resources (Menold *et al.*, 2019). A supportive method is needed to conceptualize a more resource sparing way of validation. This is where SE becomes important in this context. Previous work has already shown that an integrative view of SE and validation is of great interest (Humpert *et al.*, 2023c).
Using the system architecture is a useful validation tool to bridge the gap between requirements engineering and detailed 3D models as prototypes in the later stages of development. Validation based on the system architecture should ensure that the system developed meets the customer's intended requirements. In this way, a solution is developed iteratively to provide the greatest benefit to the user and other stakeholders. As the state of the art shows, this is not yet the standard in practice. The potential for validation based on system architecture has been identified, particularly in the Business-to-Business (B2B) sector, and needs to be addressed (Humpert *et al.*, 2023a).
For this reason, examples from special purpose machinery are used for evaluation. More complex products and an increasing number of requirements make new approaches even more essential. The question to be answered is how to approach validation using the system architecture (Humpert *et al.*, 2023a). The MoSyS research project on human-centered design of complex systems of systems also demonstrates this. It was the source of the approach that was then evaluated in the SE-HILFE transfer project, as described in chapter five. The focus of this paper is on validation with the customer and user in the early stages of product development using the system architecture to support small and medium-sized enterprises (SMEs) in their digitization efforts and new product development.

3. State of the art

Validation is the process of confirming and providing tangible evidence that a design element provides a system that is fit for purpose in the environment for which it was designed (INCOSE, 2022). "Have

https://doi.org/10.1017/pds.2024.263 Published online by Cambridge University Press

we developed the right system? Is the customer satisfied?" (Daigl and Glunz, 2016; Verein Deutscher Ingenieure, 2021). Answering these questions early on is only possible through validation. It involves checking the current state of the development and whether it will continue to meet the requirements of the customer and other stakeholders (Verein Deutscher Ingenieure, 2021). This includes design validation, which is the confirmation that the design will result in a system that will achieve its intended purpose in its operational environment when operated by its intended users (INCOSE, 2022). It requires the continuous involvement of customers, users and other stakeholders (INCOSE, 2023).

There are three aspects that play a role in validation and its purpose, according to Kelley and Kelley. These are grouped under the three lenses of innovation: Desirability, Feasibility, and Viability (Kelley and Kelley, 2013). The intersection of Desirability and Feasibility of the customer or other stakeholders is the subject of this paper.

Advances in SE and modelling techniques have therefore led to new approaches in comprehensive validation of complex engineering systems.

The following areas of the state of the art are relevant to the approach. First, the existing validation measures in the product development process are analyzed (cf. chaper 3.1). Then, approaches are shown that take the system architecture into account in the validation process (cf. chapter 3.2). In the next step, modelling approaches and languages relevant to the paper's approach are identified (cf. chapter 3.3).

3.1. Approaches for validation in the development process

The V-model (Verein Deutscher Ingenieure, 2021) is primarily used as the development process for mechatronic systems. According to the V-model, the phases in the development process are classified according to the V-model (Verein Deutscher Ingenieure, 2004; Verein Deutscher Ingenieure, 2021). The areas of requirements (requirements elicitation), system design (system architecture), domain-specific design (implementation of system elements), system integration (system integration & verification), and property validation (validation & transition) are considered separately as a phase (Gausemeier *et al.*, 2019).

The V-model highlights continuous validation with the stakeholder (INCOSE, 2023). It illustrates the development activities of SE during the life cycle phases (INCOSE, 2015). In the system design phase, fundamental decisions are made in the system design (IEEE, 2011). Furthermore, the system architecture is defined across disciplines as the basis for further development (Gausemeier *et al.*, 2019). The V-model aims more at planning validation for the right side of the V. Additionally it claims that validation through virtual development is possible on the left side (Verein Deutscher Ingenieure, 2021), but does not describe how it should be done. This results in rather vague guidelines on how to perform validation.

Albers describes product development on the basis of the extended ZHO-model (Albers *et al.*, 2013). This model views product development as a continuous interaction between three systems: the operating system, the target system, and the object system. A central activity in this process is validation. Validation compares both the object system and the target system with actual requirements and future use cases (Henning and Moeller, 2011). Validation consists of three activities: Evaluation as the examination of the elements of the object system from the stakeholder's point of view. Objectification as the identification of potentials to increase the objectivity of the target system and verification as the comparison of elements of the object system with elements of the target system (Albers *et al.*, 2016).

A verified system is assumed in this paper.

The validation process, according to Gräßler and Oleff (Gräßler and Oleff, 2022), is divided into three activities - planning, implementation, and management of the validation. When planning the validation, the constraints and requirements for the validation, as well as the validation procedure are defined. Validation is performed once the system is operational. This applies to all levels of the system hierarchy. The management of the validation results includes the adaptation of the validation process as needed and the documentation required for traceability. This process forms the basis for the validation approach in chapter four. There are other validation methods that are only integrated into the development process. This includes validation methods such as focus groups or concept tests (Knöchel, 2017). Validation methods that can be used in the B2B sector as well as in system design have been presented in an analysis (Humpert *et al.*, 2023b).

https://doi.org/10.1017/pds.2024.263 Published online by Cambridge University Press

3.2. Validation approaches in the context of system architecture

In addition, a systematic literature review (Humpert *et al.*, 2023c) has shown that there is a wide range of literature that connects the issues described above: (Dani *et al.*, 2022; Speck *et al.*, 2015; Mandel *et al.*, 2021; Barosan and van der Heijden, 2022; Ramos *et al.*, 2013). For example, Mandel et al. include an ontology of terms and how they relate to validation. Nevertheless, they do not present the topic in a comprehensive way in the sense of a validation with defined stakeholders. Rather, they address a human-oriented framework for the designer. The LITHE methodology (Ramos *et al.*, 2013) is an agile, model-based systems engineering methodology that emphasizes continuous communication, feedback, stakeholder involvement, short iterations, and rapid response. It aims to develop successful systems that meet stakeholder expectations and consider the integration of human systems. The LITHE methodology addresses the entire lifecycle, but it does not address the B2B sector and system architecture integration. According to Barosan and van der Heijden, a method is presented for converting models to 3D using extraction, communication, and data processing modules in a conversion layer. A prototype implementation is presented, but further research is needed. Future work aims at improving the 3D representation according to planned steps. However, consistent and coherent models are required, and the language or level of detail is not specified. In addition, there is no indication of the time it takes to create a 3D model (Barosan and van der Heijden, 2022). In particular, the B2B sector and related areas are poorly, hardly or not at all represented in the above contributions.

3.3. Modelling languages for validation

Particularly, modelling languages and approaches have evolved. In addition to the Unified Modelling Language (UML), Systems Modelling Language (SysML) or CONceptual design Specification technique for the Engineering of complex Systems (CONSENS), a SysML v2 with unique semantics has emerged to capture and represent system architectures (INCOSE, 2015). The system architecture includes the relationships between requirements, functions, logical and physical structure. These can be visualized using various tools such as the Cameo Systems Modeler or iQUAVIS.

The research conducted on modelling languages and approaches in SE shows that the selection process should be guided by the specific requirements of the user, such as reusability, learnability, usability, redundancy or consistency of a modelling language (Wilke *et al.*, 2024b). It is important to note that not all languages and approaches can fulfil every criterion. Therefore, a comparative framework has been proposed to assist users in making an informed decision. This framework serves as a valuable resource in the selection process. One of the viable options that emerged from this research, particularly for special purpose machinery, is the Arcadia or LITHE approach, which fits well with the criteria considered. Interestingly, the CONSENS approach received the highest score. However, it is worth noting that LML is also considered a good language, as it considers the user-specified criteria and appears to meet most of these. The language and method must be adapted to the company and the customer. It enables intuitive and user-friendly communication between modelers and other stakeholders (Humpert *et al.*, 2023a; Wilke *et al.*, 2024a).

4. Approach

The main part of the paper, the approach, is presented in this chapter. Since many companies today still develop according to the stage-gate model or the V-model, this approach is particularly interesting for system design, i.e., the early phases of product development. The approach is integrated into the product development process within an agile approach and primarily affects the systems engineer and validation engineer of a company according to the roles of Könemann *et al.* (2022). Due to the technical understanding of the customer in the B2B sector, the approach mainly concerns this industry (Humpert *et al.*, 2023c). Therefore, the goal is to increase the accuracy of the development through validation in the early phases of product development.

The developed process (cf. Figure 1) consists of three phases, each with several steps. It follows the general principle of validation according to Gräßler and Oleff (Gräßler and Oleff, 2022). The first phase of the proposed approach helps in gathering the required stakeholders and the validation approach. It also establishes the architecture required for validation (cf. chapter 4.1). In the second phase, the

https://doi.org/10.1017/pds.2024.263 Published online by Cambridge University Press

validation approach is performed with the relevant stakeholders. The selected partial models of the system architecture are analyzed and changes are incorporated (cf. chapter 4.2). The third phase focuses on documentation and changes to the system architecture including requirements (cf. chapter 4.3).

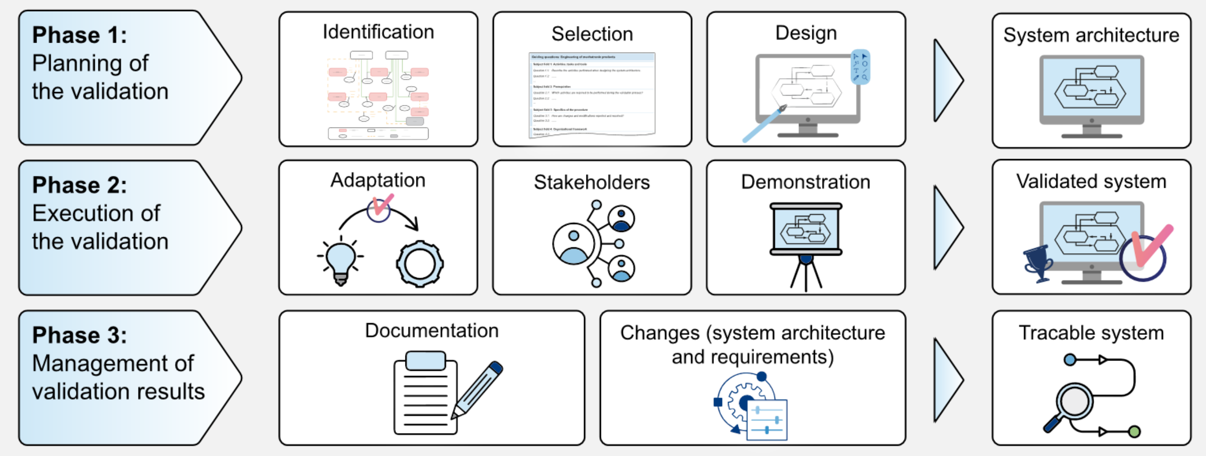

Figure 1. Approach for validation using the system architecture

4.1. Planning of the validation

The first phase consists of three steps. After identifying and analyzing the stakeholders, the validation approach is selected. Then the system architecture is created according to certain design rules.
Step 1 – Stakeholder identification und analysis: Analogously Humpert *et al.* (2023a), a stakeholder map of the customer is set up by the validation engineer or systems engineer. The relevant stakeholders are identified and the number of stakeholders is taken into account. A subdivision of the stakeholders enables the selection of the participants during the second phase. It is important not only to identify the structure of the stakeholders at the customer, but also to consider which stakeholders are accessible for validation. For example, the user of the system in the B2B sector is not always accessible as a stakeholder for validation, since the product is often resold.
Step 2 – Selection of the validation approach: A preliminary selection of validation approaches has shown that the following validation approaches can be considered for system design and the B2B sector: Customer Idealized Design, Conjoint Analysis, Category Appraisal, Voice of the Customer (VOC), Concept Tests, Beta Tests, Customer Feedback, Lead User Concept, Focus Group, Co-Development, Randomized Controlled Studies, Scenario Tests, Usability Testing, and Reviews. This has resulted in fact sheets from which to choose. A validation method can then be selected on a company-specific basis.
Step 3 – Designing the system architecture: This is the focus of the approach. The analysis of the modelling languages has shown that a different modelling language can be chosen depending on the industry and the use case. Depending on the customer and his previous experience, it may be necessary to change the modeling language and approach. It is essential to adapt this to the company.
In addition, the following guidelines have been developed for user orientation and system architecture design. The guidelines are evaluated with experts and taken into account when creating the system architecture for validation. Mainly guidelines for the design are integrated (Alt, 2012; Douglass, 2021; Kaiser, 2014; IEEE, 2011):

- Views: First, the architecture views that cover the different aspects of the system for validation must be selected. Examples are the environment diagram, the effect structure or the activity diagram.
- Simplicity: the architecture should be designed as simple as possible, a guideline here is seven plus or minus two modelling elements in each diagram. This is due to the human ability to remember information (Glaser, 2019).
- Levels of abstraction: Again, to reduce the complexity of the system structure, seven plus or minus two elements are targeted. The system should be divided into several modules.

https://doi.org/10.1017/pds.2024.263 Published online by Cambridge University Press

- Documentation: Finally, the system architecture must be documented for implementation. This should allow the stakeholders to better understand it. For example, the way it is presented is also important. Accordingly, documentation can be done non-formally with workshops, for example, or formally with various modelling tools, such as iQuavis (Schierbaum, 2019).
- Reusability: the system architecture must be designed to contain reusable components and modules. This allows for more efficient development and facilitates future enhancements or customizations.
- Consistency: Ensure that the different views of the system architecture are consistent and complementary. There should be a clear relationship between the elements in the views.
- Scalability: When designing the system architecture, the scalability of the system must be considered. It should be ensured that the system is scalable as requirements grow.
- Timeliness: Before and after validation, it is necessary to ensure that the system architecture and requirements are up to date in order to adapt the validation to the temporal status of the system's development.

4.2. Execution of the validation

Validation is executed in phase two. In total, the outcome here is the validated system.
Step 1 – Adaptation of the validation approach: The choice of validation method in Phase 1 needs to be adapted to the specific situation of the organisation and the people who will be performing the method at the time of implementation. For example, the duration of the method plays a role or whether the validation must be done virtually or in person. In the case of a concept test, the system architecture is presented to the stakeholders as a concept or subconcept.
Step 2 – Involvement of the relevant stakeholders: In the second step, the relevant stakeholders are involved in the approach. Based on the stakeholder analysis and map, the stakeholders who are available and relevant for the type of problem are invited.
Step 3 – Demonstrating the system architecture: The system architecture presented consists of selected diagrams that are relevant to the stakeholders and, for example, a change in requirements. These are then reviewed with the stakeholder and changes are recorded. Targeted questions should help the stakeholder to understand the areas shown and to express further requirements.

4.3. Management of the validation results

This third phase creates a traceable system that is validated and can be adapted to changes in customer requirements.
Step 1 – Documentation: The results are extracted from the recording and the resulting requirements for the system are documented. This can be done on paper or directly in a tool.
Step 2 – Changing the system architecture and requirements: The requirement changes and further notes of the stakeholders are documented after the implementation. Ideally, the system architecture should exist in a tool such as the Cameo system modeler or iQUAVIS, where the requirements and thus the system architecture can be adapted. With regard to changing the requirements, a sentence template helps to represent the needs of the stakeholders in a framework that is systematized for the development. The approach can be repeated as often as required in an agile framework during system design development. Following this phase of development, validation is usually performed with prototypes.

5. Application of the approach

This chapter describes the prescriptive study and evaluates the approach presented above.
The system architecture validation approach was developed in the MoSyS project (Human-centred Development of System of Systems) and validated in the it's owl transfer project SE-HILFE (SE for the offer phase for special developments). The validation carried out as part of the transfer project is described in the following section. The approach is executed with the technical sales department of a special purpose machine manufacturer and a fictive customer. The offer phase is considered and appropriate diagrams for communicating with customers at this stage are highlighted.

https://doi.org/10.1017/pds.2024.263 Published online by Cambridge University Press

In this early phase of development, the approach is primarily used to record requirements, whereas later it is used to detect changes in requirements. The approach was therefore tested on two complex mechatronic systems; a machine tool as a fictional example and a custom machine as a real industrial example. These examples are complex B2B mechatronic systems with different systems architectures. As a side note, another example of an Artificial Intelligence (AI) use case is presented at the end. Using this example, the approach should be extended to non-mechatronic systems. For the sake of simplicity, the description of the execution for the custom built machine is described. The further example was carried out in the same way. In this case we focus on the modelling method and language CONSENS, as this had a strong evaluation in the analysis of chapter 3.3. CONSENS was selected on the basis of various analysis criteria relating to learnability and user-orientation as a human-oriented language and approach for this application and the circumstances of special purpose machinery. According to Schierbaum (2019), Gausemeier *et al.* (2019), Bremer (2020) and the execution of the approach, only selected partial models (see chapter 5.1) of CONSENS are considered for validation. They address the problem and solution space in the lead development phase. In contrast, the behaviour (relevant only in the later phases) is not considered, since this is the dynamic view of the active structure (Gausemeier *et al.*, 2019). The resource diagram details the process diagram and the shape contains a certain amount of effort to produce for validation and therefore resources that need to be saved first. The diagrams of the service design and further diagrams of the production system conception are excluded for the time being, since these represent likewise a product.

5.1. Phase 1 — Planning of the validation

In the first step, a stakeholder map was created and the relevant type and number of stakeholders were listed. In step 2, a concept test was chosen as the validation method with the help of the fact sheets. In consultation with sociology experts, this validation method is primarily recommended for this example. The system architecture was designed according to the requirements using the modelling language and approach CONSENS, as CONSENS was rated as a very helpful method (Wilke *et al.*, 2024a). The colours and simplicity of the diagrams make it easier for the user to understand. In contrast, SysML is a standard language for SE, but with a certain complexity. An environment model, a function hierarchy, a process, an active structure, and application scenarios were created (Figure 2). The environment model is used to discuss the environment of the system with the customer. The functional hierarchy is used to illustrate and structure the main functions. The process flow diagram is used to illustrate the sequential order of processes in the system, e.g. for cycle time calculations. The active structure is used to identify individual components that do not meet the customer's requirements. The application scenario diagrams are used to illustrate and discuss various possible use cases of the system. They help to understand the requirements and needs of the users.

5.2. Phase 2 — Execution of the validation

The first step involved adapting the validation approach. A concept test was chosen. The fictive customer and two technical sales representatives were involved in Phase 2. The diagrams and questions were presented and discussed one by one in step 3. The expressions of the stakeholders were recorded.

5.3. Phase 3 — Management of the validation results

The result was documented and evaluated accordingly. The evaluation was scanned for further requirements and corrections. Subsequently, the result is incorporated into the system architecture in phase 2, thus starting the next development step. In addition, another example of a software product - an AI use case - is presented. The MoSyS project consortium developed an AI application for common parts management to assist designers in the development of a special purpose machine. Stakeholders in phase 2 included five users (designers) of the AI application and the corresponding management. To be able to rank the effectiveness of the approach, requirement changes were identified in this test case at this stage of development, which affected 30 percent of the requirements. After developing the application using mock-ups and a prototype, the application was implemented. With the help of user tests, the AI application was tested for its usability. Subsequently, a SUS and SUMI questionnaire were

https://doi.org/10.1017/pds.2024.263 Published online by Cambridge University Press

used for evaluation, which showed that the application was very good in these aspects. This shows an initial effectiveness of the approach.

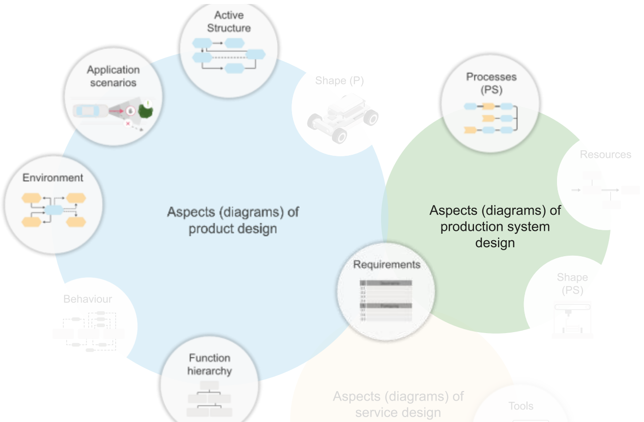

Figure 2. Diagrams in CONSENS

6. Discussion

Dividing the approach into different phases and steps provides guidance and orientation. The discussion focuses on the results of the evaluation and the views of the participants. Once the approach has been applied, a survey of the individual diagrams is carried out with the evaluation company. They were asked which types of diagrams the company considered appropriate and why. Participants indicated whether they saw no benefit, medium benefit, or high benefit. For all five types of diagrams (see chapter 5.1), the approach is seen as having a high benefit, supporting customer communication to a high degree through transparency, and being suitable for internal communication. The approach helps to react to new requirements and to recognize changes in requirements, thus saving resources. However, customer dependency is seen, i.e., there are customers and users for whom the approach works better based on an expectation and for whom it works worse. For all diagram types, a benefit is seen in the offer phase and in system design. For detailed engineering, the use of these diagrams is limited, as in some cases a higher level of detail is required. The function hierarchy is seen as a communication tool, especially in system design. However, this was more of an internal help for the company. The process flow is important to detail the processes of a machine, to find functions and especially to address new customers. The environment model mainly considers the changes of the customer in the environment. In addition, the environment model is also strongly seen as an interface between the offer phase and the system design. For the active structure, the level of detail in the early phases is particularly important and must not be too high. A limitation of the approach is the limited 2D representation. With additional information from later development phases, a 3D representation can be achieved and a integration of prototyping methods for validation can help. In summary, some sub-models are more suitable than others, and different sub-models are needed depending on the company. The initial situation of the company is also crucial, as well as the experience of the stakeholders with a system architecture. This means that both the company and the customer are influencing factors for the success of the approach.

7. Conclusion and future work

This paper presents a validation approach based on system architecture. The aim of this approach is the early detection of requirement changes and errors, thus saving resources which helps achieving the European climate goals. In the first phase, the validation is prepared and the validation method is selected. In the second phase, the system is validated with the appropriate system architecture and stakeholders. Finally, the implementation is followed up and changes in requirements are documented. The significance of the paper is in linking CONSENS diagrams with corresponding benefits and demonstrating the precise application of the validation approach through design rules.

The way elements are displayed in system architecture diagrams from a usability perspective will be important for further research. It is also important to consider whether 3D models can be provided for

https://doi.org/10.1017/pds.2024.263 Published online by Cambridge University Press

validation at this stage of development. It must be taken into account that limited resources are available and that these should be linked to the system architecture. In the future, we should also look at other B2B sectors in addition to mechanical engineering and examine the transferability of our results. It is therefore necessary to clarify how many resources can be saved with this approach.

Acknowledgment

This article is part of the research project MoSyS - Human-Oriented Design of Complex Systems of Systems. This project is funded by the German Federal Ministry of Education and Research (BMBF) within the “The Future of Value Creation – Research on Production, Services and Work” program (funding number 02J19B106) and managed by the Project Management Agency Karlsruhe (PTKA). The authors are responsible for the content of this publication. This research and development project is/was funded by the Ministry of Economy, industry, climate action and energy of the State of North Rhine-Westphalia (MWIKE) in the context of the Leading-Edge Cluster ‚Intelligent Technical Systems OstWestfalenLippe (it‘s OWL)‘ and super-vised by Project Management Jülich (PtJ). The responsibility for the content of this publication lies with the author.

References

Albers, A., Behrendt, M., Klingler, S. and Matros, K. (2016), “Verifikation und Validierung im Produktentstehungsprozess”, in Lindemann, U. (Ed.), Handbuch Produktentwicklung, Carl Hanser Verlag GmbH & Co. KG, München, pp. 541–569. https://doi.org/10.3139/9783446445819.019.

Albers, A., Behrendt, M., Schroeter, J., Ott, S. and Klingler, S. (2013), “X-in-the-loop: A framework for supporting central engineering activities and contracting complexity in product engineering processes”: ICED 13, the 19th International Conference on Engineering Design, Sungkyunkwan University (SKKU), Seoul, Korea, August 19-22, 2013, Design Society, Castle Cary, Somerset.

Alt, O. (2012), Modellbasierte Systementwicklung mit SysML, Carl Hanser Fachbuchverlag, München. https://doi.org/10.3139/9783446431270.

Barosan, I. and van der Heijden, J. (2022), “Integration of SysML models in a 3D environment for Virtual Testing and Validation”, Proceedings of the Federal Africa and Middle East Conference on Software Engineering, Cairo-Kampala, Egypt, June 7-8, 2022, Association for Computing Machinery, New York, pp. 39–45. https://doi.org/10.1145/3531056.3542784.

Blessing, L.T. and Chakrabarti, A. (Eds.) (2009), "DRM, a Design Research Methodology", Springer London. https://doi.org/10.1007/978-1-84882-587-1.

Bremer, C. (2020), Systematik zur Modellierung flexibler Produktionsanlagen im Model-Based Systems Engineering, [PhD Thesis], Paderborn University.

Daigl, M. and Glunz, R. (2016), ISO 29119 - Die Softwaretest-Normen verstehen und anwenden, dpunkt.verlag, Heidelberg.

Douglass, B.P. (2021), Agile model-based systems engineering cookbook: Improve system development by applying proven recipes for effective agile systems engineering, Packt Publishing, Birmingham, Mumbai.

Europäische Kommission (2023), Der grüne Industrieplan. [online] Europäische Kommission. available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan_de (accessed 28 September 2023).

European Commission (2023), A Green Deal Industrial Plan for the Net-Zero Age, European Commission, Brussels, Belgium.

Fischer, N. and Salzwedel, H. (2012), “Validating Avionics Conceptual Architectures with Executable Specifications”, Systemics, Cybernetics and informatics, Vol. 10 No. 4, pp. 46-55.

Gausemeier, J., Dumitrescu, R., Echterfeld, J., Pfänder, T., Steffen, D. and Thielemann, F. (Eds.) (2019), Innovationen für die Märkte von morgen: Strategische Planung von Produkten, Dienstleistungen und Geschäftsmodellen, Hanser, München.

Glaser, C. (2019), “Millersche Zahl”, In: Glaser, C. (Ed.), Risiko im Management, Springer Fachmedien Wiesbaden, Wiesbaden, pp. 53–56. https://doi.org/10.1007/978-3-658-25835-1

Gräßler, I. and Oleff, C. (2022), Systems engineering: Verstehen und industriell umsetzen, Springer Vieweg, Berlin. https://doi.org/10.1007/978-3-662-64517-8_1

Henning, F. and Moeller, E. (Eds.) (2011), Der Prozess der Produktentstehung, Carl Hanser Verlag GmbH & Co. KG, München. https://doi.org/10.3139/9783446428911.001

Humpert, L., Röhm, B., Anacker, H., Dumitrescu, R. and Anderl, R. (2022), “Method for direct end customer integration into the agile product development”, Procedia CIRP, ELSEVIER, Vol. 109, pp. 215–220.

Humpert, L., Wäschle Moritz, Horstmeyer Sarah, Anacker, H., Dumitrescu, R. and A. Albers (2023a), “Stakeholder-oriented Elaboration of Artificial Intelligence use cases using the example of Special-Purpose engineering”, 33rd CIRP Design Conference, ELSEVIER, Vol. 119, pp. 693-698.

Humpert, L., Wilke, D., Anacker, H., Dumitrescu, R. and Tissen, D. (2023b), „Investigation of validation methods for system design in the B2B sector“, Accepted, SysCon, Montreal, 2024

Humpert, L., Zagatta, K., Anacker, H. and Dumitrescu, R. (2023c), “Identification of fields of action for validation in Systems Engineering”, IEEE International Conference on Technology Management, Operations and Decisions (IEEE ICTMOD), Rabat, Morocco, November 22-24, 2023, IEEE.

IEEE (2011), ISO/IEC/IEEE 42010 Systems and software engineering — Architecture description.

INCOSE (2015), Systems engineering handbook: A guide for system life cycle processes and activities, Fourth Edition, Wiley, Hoboken, N.J.

INCOSE (2022), “Guide to Verification and Validation. May 2022”.

INCOSE (2023), INCOSE Systems Engineering Handbook, 5th ed., John Wiley & Sons Incorporated, Newark.

Kaiser, L. (2014), Rahmenwerk zur Modellierung einer plausiblen Systemstruktur mechatronischer Systeme, [PhD Thesis], Paderborn University.

Kelley, T. and Kelley, D. (2013), Creative confidence: Unleashing the creative potential within us all, William Collins, London.

Knöchel, M. (2017), Kundeneinbindung Im Innovationsprozess - Methoden, Essentials, Springer Gabler, Wiesbaden. https://doi.org/10.1007/978-3-658-20427-3_6.

Könemann, U., Wilke, D., Anacker, H. and Dumitrescu, R. (2022), “Identification of stakeholder-specific Systems Engineering competencies for industry”, 2022 IEEE International Systems Conference (SysCon), Montreal, Canada, April 25-28, 2022, IEEE, pp. 1–7. 10.1109/SysCon53536.2022.9773861

Mandel, C., Boning, J., Behrendt, M. and Albers, A. (2021), “A Model-Based Systems Engineering Approach to Support Continuous Validation in PGE - Product Generation Engineering”, 2021 IEEE International Symposium on Systems Engineering (ISSE), Vienna, Austria, September 13- October 13, IEEE, pp. 1–8.

Menold, J., Simpson, T.W. and Jablokow, K. (2019), “The prototype for X framework: exploring the effects of a structured prototyping framework on functional prototypes”, Research in Engineering Design, Vol. 30 No. 2, pp. 187–201. https://doi.org/10.1007/s00163-018-0289-4.

Ramos, A.L., Ferreira, J.V. and Barcelo, J. (2013), “LITHE: An Agile Methodology for Human-Centric Model-Based Systems Engineering”, IEEE Transactions on Systems, Man, and Cybernetics: Systems, Vol. 43 No. 3, pp. 504–521. https://doi.org/10.1109/TSMCA.2012.2207888.

Schierbaum, A.M. (2019), Systematik zur Ableitung bedarfsgerechter Systems Engineering Leitfäden im Maschinenbau, [PhD Thesis], Paderborn University.

Speck, A., Witt, S., Feja, S. and Pulvermüller, E. (2015), “Tool-based checking of business process models”, in Ehlers, J. and Thalheim, B. (Eds.), Proceedings of the 7th International Conference on Subject-Oriented Business Process Management, Kiel, Germany, April 23-24, ACM, New York, NY, USA, pp. 1–8. https://doi.org/10.1145/2723839.2723848.

Stein Dani, V., Freitas, C.M.D.S. and Thom, L.H. (2022), “Recommendations for visual feedback about problems within BPMN process models”, Software and Systems Modeling, Vol. 21 No. 5, pp. 2039–2065.

Verein Deutscher Ingenieure (2004), VDI-Richtlinie VDI 2206: Entwicklungsmethodik für mechatronische Systeme.

Verein Deutscher Ingenieure (2021), VDI-Richtlinie VDI 2206: Entwicklungsmethodik für mechatronische Systeme.

Verein Deutscher Ingenieure (VDI) (2018), Ressourceneffizienz in kleinen und mittleren Unternehmen (KMU): Strategien und Vorgehensweisen zum effizienten Einsatz natürlicher Ressourcen.

Verein Deutscher Ingenieure (VDI) (2023), Ressourceneffizienz und Ressourcenschonung: Methodische Grundlagen, Prinzipien und Strategien.

Wilke, D., Humpert, L., Mansheim, J., Anacker, H. and Dumitrescu, R. (2023), “Systems Engineering Potentials and Use Cases for the Offer Phase in Special Purpose Machinery”, Proceedings of the 34th Symposium Design for X (DFX2023), Radebeul, Germany, September 14-15, 2023, The Design Society, pp. 225–234. https://doi.org/10.35199/dfx2023.23.

Wilke, D., Humpert, L., Seidenberg, T., Menne, L., Grewe, C., Dumitrescu, R. (2024a), "MBSE as an enabler for collaborative offer management for individual production systems". Accepted, SysCon, Montreal, 2024

Wilke, D., Humpert, L., Suwal, P., Anacker, H. and Dumitrescu, R. (2024b), “Framework for the selection of Systems Engineering modelling languages and methods in special purpose machinery”. Unpublished, NordDESIGN 2024, Reykjavík, Iceland, August 12-14, 2024, The Design Society.

https://doi.org/10.1017/pds.2024.263 Published online by Cambridge University Press