Evaluation of different Systems Engineering Approaches as Solutions to Cross-Lifecycle Traceability Problems in Product Development: A Survey

Sina Hajiaghapour
Department of Product Safety and Quality
University of Wuppertal
Wuppertal, Germany
e-mail: hajiaghapour@uni-wuppertal.de

Nadine Schlueter
Department of Product Safety and Quality
University of Wuppertal
Wuppertal, Germany
e-mail: Schlueter@uni-wuppertal.de

***Abstract*— Requirements traceability is an essential Systems Engineering (SE) task that is critical in areas such as software development, product development, and safety engineering. It involves linking requirements to all system elements, including test cases, to improve test coverage, product quality, and communication among stakeholders. Due to limitations in SE approaches underlying traceability methods, this area faces challenges such as an imbalance between cost and quality or insufficient system understanding for different disciplines. In this paper, we examine several universal SE approaches for their efficiency in addressing traceability issues in product development. Through a literature review, we identified methods based on these approaches and evaluated their effectiveness in solving traceability problems. This survey demonstrates the potential of Generic Systems Engineering (GSE) based methods to address identified gaps by creating a universal system understanding. However, the modelling method and procedure concept used in these approaches requires the inclusion of test processes and the associated information for system testing.**

Keywords-System Engineering; Requirement Engineering; Traceability; System Test; Product Development.

I. INTRODUCTION

According to the definition of INCOSE (International Council on Systems Engineering), System Engineering (SE) is an approach that aims to enable system designers to capture and meet customer and stakeholder requirements for the system throughout its life cycle, through better traceability of issues and more efficient coordination in an interdisciplinary team [1]. This definition makes it clear that capturing, structuring, and implementing requirements for the system and its elements are also part of SE. Thus, "Requirement Engineering (RE)" is referred to as a subdiscipline of SE [1][2]. RE includes all activities necessary to elicit, analyze, and document (product and project) requirements. In the RE process, requirements are not only developed but also iteratively managed [3]. Thus, this process can be divided into two parts, i.e., Requirement Development and Requirement Management (RM) [4][5].

System requirements are constantly changing due to changes in the needs of system stakeholders (including customers), changes in the environment, changes in the business, changes in laws and regulations, etc. [4][6]. RM is primarily the process of controlling these "changes" to system requirements. In this respect, however, RM is facing new challenges. The current high level of globalization is closing to Enterprise Networks (EN) with multidisciplinary teams. A short reaction time to the changes and thus the fulfillment of customer requirements needs a more complex cooperation between the different internal departments as well as external companies [4][7]. Minimization of failure, adherence to schedules, and high product quality require not only a common understanding of the system design, but also information about the required quality standards and the current data situation among all team members [8]. Nevertheless, this cannot be realized without the creation of efficient interdepartmental data exchange mechanisms and communication capabilities or interfaces for recording information. An essential necessity is the capability to trace requirements in both retrospective manners (such as identifying the source of a requirement) and prospective manners (like associating test cases). In other words, traceability in a system should include the relationship between requirement and all system elements including **components**, **processes**, **functions**, and **test cases** [2][4]. Finally, in order to capture and map responsibilities for various system elements in the EN, the requirements and the above mentioned system artifacts should be linked to the responsible **persons** [9][10].

As mentioned above, requirements traceability should also be used to link requirements to test specifications and methods. It is important to know which requirement is covered by which test or test cases. In addition to mentioning important benefits of merging requirements and test cases, Kukkanen et al. have illustrated the important relationships between the processes of RE and System Testing (ST) in their work [11]. In [12]-[15], further advantages of linking requirements and testing are mentioned.

A. *Traceability Challenges and Problems*

Requirements traceability can be influenced by several factors. Ramesh identifies three factors that affect the implementation of requirements traceability in a company, namely the environment (technologies), the organization (business strategies), and the context of system development (policies, people) [16]. These three factors can in turn be divided into two coarser categories of **methods** and (tracing) **tools** [17][18].

Appropriate and practical methods are needed to track requirements, including their linkage to test methods, which at the same time allow a cost-quality trade-off [19]. Graham

 ISBN: 978-1-68558-088-9

has also identified the absence of the physical end system prior to the development and planning of the test methods as one of the seven problems in linking requirements and testing [20]. The development process of complex meta-systems or more specifically “system of systems (SoS)” consisting of various components, is an interplay of various specialist disciplines. Here, in addition to bringing these disciplines together and linking the respective experts for the purpose of smooth communication and information transfer, methods and measures are also required to master the complexity of the multi-structural design of the overall system for effective uniform system understanding among the stakeholders [21]. However, such standardized procedures with a trade-off between cost (including time) and quality for analyzing requirements and translating them into a clear model do not yet seem to be widely used in industry [14][22]-[26].

Finally, the appropriate model-based method should be implemented in a computer-based tool, namely tracing tool, which plays an important role in the context of traceability [27]-[29]. A lack of suitable tools also leads to a mismatch between requirements and customer needs, which affects customer satisfaction with the final product [30]. Nevertheless, the efficiency of traceability and thus RM in the state of the art is limited due to lack of tool support [11][12][16][24][25][31]-[37]. The willingness of corporate employees to learn and use the tool depends heavily on the degree to which the tool is user-friendly [17]. This can be a particular barrier for Small and medium-sized enterprises (SMEs) that have limited infrastructure for using complex tools and organizing the necessary training [38]-[43].

The above factors show the need for a method that improves system understanding through an appropriate metamodel in an efficient and cross-lifecycle manner, as well as a smooth flow of information in EN through a powerful tool. This is exactly the main goal of SE mentioned earlier in this paper, where the system model should not only enable an interdisciplinary product view, but also support communication and cooperation between users and provide a link between different system data [10]. By linking the system model to a procedure concept, SE is also intended to represent the temporally logical linking of problem-solving steps to solve a complex task. Nevertheless, due to limitations in SE approaches underlying traceability methods, the identified challenges remain unsolved. The main problem is the loss of the original idea of SE over time, i.e., the merging of different disciplines due to the increasing focus on specific areas instead of universality of methods [44]. This can degrade communication in a multidisciplinary team, for example between requirements and test engineers, which is one of the important problems of traceability. In addition to briefly presenting various SE approaches, the following part introduces some of these constraints.

B. *Different SE Approaches*

The approaches developed for SE can be categorized as either universal or specific [45]. The specific SE approaches, e.g., for software engineering focus on their own disciplines and not on the universal transdisciplinary use that should characterise SE. This makes it difficult to communicate between disciplines and to identify commonalities in their methods. The methodological differentiation of such approaches hinders transferability between different product domains and slows down the product development process [46]-[48]. However, this is of great importance for the development process of meta-systems, which represent a multitude of different technical subsystems from the various domains, as mentioned above.

The universal approaches can be divided into System of Systems Engineering (SoSE), Model-Based System Engineering (MBSE) and Generic System Engineering (GSE) [49]. Various descriptions of SoSE or SoS have been produced in the literature, but to date there is no universally accepted definition [50]-[54]. In the absence of a general system definition, the domains, relationships and attributes cannot be represented in a uniform way, which hinders the creation of a unified system model [45].

INCOSE defines Model-Based Systems Engineering (MBSE) as a "formalized application of modelling to support system requirements, design, analysis, verification, and validation that begins in the conceptual phase and extends throughout development and later life cycle phases“ [55]. Within the context of MBSE, numerous modeling languages are utilized. In practice, the models based on the "Unified Modeling Language (UML)" and "System Markup/Modelling Language (SysML)" have become the most popular in the MBSE application. These are capable of representing the relationships between system elements and requirements, but exhibit a high level of abstraction, primarily stemming from their limited graphical notation [56]. Moreover, this approach lacks interaction between the system model and the procedure model at each step of the development process. This is of course needed for updating the system model as well as for traceability of elements over time, as dynamic environmental factors need to be taken into account [2][57]. According to Morkevicius et al. many methods in the context of MBSE remain too abstract for solving concrete real-world problems because they do not provide a framework for organizing the modelling work [58]. Such methods show a mismatch between the model created and the expectations of customers, as understanding the system is difficult for different stakeholders due to the high model complexity [59]. Another limitation of MBSE methodologies is finding a common language for defining stakeholder needs and bringing together a wide range of stakeholder views into a single model [60][61]. In addition, INCOSE cites inherent difficulties in integrating models across organizational, lifecycle and other boundaries, and limitation of model/data sharing capabilities within modelling tools as other problems of MBSE [55][60][62]. Moreover, the high implementation costs of MBSE approaches compared to traditional SE approaches and the still limited life-cycle management tools for managing MBSE models [59][62]-[65] can be particularly challenging for SMEs. In the case of highly complex technical systems, the lack of a transdisciplinary focus and the difficulties in managing a large amount of generated data are further problems of the MBSE approach [2][66].

 ISBN: 978-1-68558-088-9

"Generic System Engineering (GSE)" developed by Winzer and Sitte [67] is considered a state-of-the-art and proven approach that satisfies the new dimensions of complexity, thus reviving the lost original universal approach of SE [45][46][49][57]. GSE proposes a common thinking model to derive a unified system model. For this purpose, it consists of a standardized approach divided into the "analysis" (problem identification and system analysis), the "target definition" (problem localization), and the "design" (recommendations), which can be problem-specific [46]. GSE standardizes SE in both system modeling and approach. GSE is thus a general problem-solving framework that provides different modules and a system model to ensure adaptation to a variety of specific problems [2][46][67]. One major advantage of the GSE approach over MBSE and SoSE is the clearly defined interface to project management [44][68]. This can contribute to a fast response to changes in system design or properties.

There are many different methods for building the system model for the technical systems and collaborative SoS in GSE, including Demand Compliant Design (DeCoDe), which provides a technique for system definition, description, modeling, and progressive refinement. The four views of the DeCoDe product model, i.e., requirement, component, function, process, are related to each other via a matrix to describe technical product systems [69]. An "enhanced Demand Compliant Design" (e-DeCoDe) integrates the social level of the SoS into the model through a fifth person view and thus enables the capture and mapping of responsibilities for different system elements in the EN [9][10]. All e-DeCoDe elements can also be represented hierarchically, with the requirements view. The unified matrix representation of the system in e-DeCoDe model can improve the understanding of the system for different disciplines by representing the system and the interaction between its elements in a simple but comprehensive manner. The low level of complication of the modeling method can be a promising factor in reducing implementation costs, as less training is required. Compared to the other modeling approaches, e-DeCoDe provides a clear delineation between system and environment and methodical handling of requirements in EN [44].

After introducing the different SE approaches and their general strengths and limitations, the different traceability methods offered in the state of the art according to the introduced universal SE approach will be surveyed in the next sections. Section II explains the methodology used in this research. Finally, the identified papers are evaluated and summarized in Section III.

II. Research Design

In this section, the aim of the study is formulated. In addition, the research questions and the methodology of the literature review are described here.

A. Objective and Research Questions

In the last section, traceability challenges were divided into two broad categories: Tools and Methods. Here, the necessary training costs for the tools and their limited functionality are the subordinate problems of the first category, i.e., traceability tools, while the trade-off between cost and quality of the approaches resulting from the complexity of the methods belong to the second category. Therefore, the objective of this work is to evaluate the existing methods in terms of their efficiency and the applicability of the tools used. This goal will be concretized in the form of different research questions (Q).

Q_1: Which approach is able to define the system more comprehensively by covering the different views of it (e.g. requirements, processes, etc.) including its socio-technical levels?

Q_2: Which approach is focused on managing complexity through a generic modeling methodology applicable in transdisciplinary teams?

Q_3: Which approach establishes the link between requirements and testing to improve RE and ST processes?

Q_4: Which approach has a structured procedure concept connected to the system model that maps the lifecycle of a system from requirements elicitation through design and construction to testing?

Q_5: Which programs are used to implement traceability methods and how do they contribute to reducing complexity?

Q_6: To what extent is the necessary information available to the system developer during requirements elicitation, system design and testing integrated into the implemented approach?

B. Methodology

By analyzing the current developed SE based methods to digital requirements management, including traceability in product development, the practical potential of the different approaches can be overlooked. The focus of these evaluations is on the ability of these approaches to robustly link test methods and requirements, as well as other key system elements, manage complexity and enabling system understanding across a multidisciplinary team. At the same time, the implementation of the method and the level of integration of the system data and information into an appropriate functional tool will be examined. Based on the challenges identified in Section I and the derived research questions in Section II, six different topic areas (T) to be considered are defined. The derived topics serve to more clearly distinguish these methods from the others and to better highlight the scientific gap. Subsequently, a literature review is conducted in December 2022 considering the following narrowing of the subject:

- Only the application of SE in the field of engineering is considered.
- Of these, only the methods from the field of product development are then considered.
- Of the various SE approaches applied in product development, only the universal SoSE, MBSE and GSE based methods are considered and analyzed.

The research is conducted via scientific databases such as GEPRIS, Google Scholar, IEEE Xplore, ScienceDirect, and SpringerLink during the observation period from 2015 to 2022. Based on this, 26 international and 4 national research projects or papers are picked out. Finally, the identified

 ISBN: 978-1-68558-088-9

researches are evaluated based on the six topic areas. The methodology of the literature review is shown graphically in Figure 1:

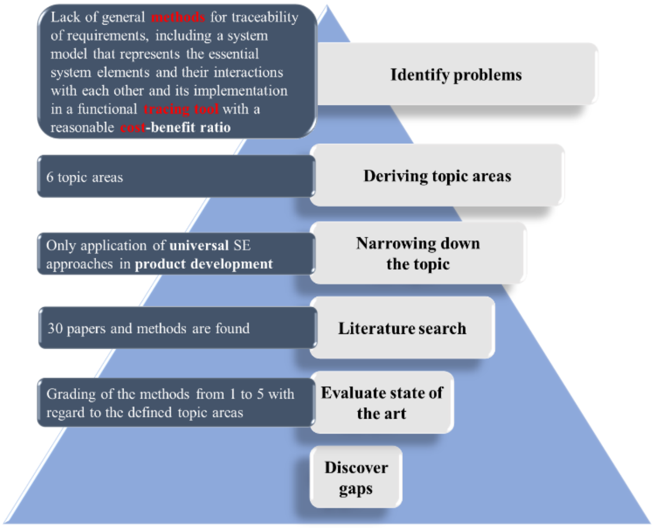

Figure 1. Graphical representation of the applied methodology in the present paper.

Based on the stated challenges and required solutions for each topic area, the studies were scored from 1 (lowest score) to 5 (highest score), with specific point awarded for each need covered. The important issues and needs for which a specific score was given are underlined in the following description of the topics with the corresponding score in parentheses. The assessment of the tools used in T_5 is based on [63][70]-[72].

T_1 (System Definition and Delimitation): The approach developed shall primarily address the linkage of requirements *(1p)* to key system parts and artifacts, including processes *(1p)* and components *(1p)*. Functional requirements shall be linked to the corresponding functions *(1p)* that the system is intended to perform. The approach should provide a clear boundary between the system and the environment and methodically support their interaction. To enable the treatment of requirements in EN, the approach should also include roles and liability through a person view *(1p)*.

T_2 (System Modeling): The developed approach should consist of a model that graphically establishes a linkage *(1p)* between the above-mentioned system elements. Generality, comprehensibility and universality of the model should be observed as well *(1p)*. By representing the interactions between these artifacts, the unified model shall enable traceability of requirements during the system development life cycle *(1p)* while handling system complexity *(1p)*. In addition, the model shall account for independent attributes and represent EN in a unified manner *(1p)*.

T_3 (Integration of Test cases): The importance and benefits of linking tests to requirements have already been explained in this paper. The model developed should be intended to enable the integration of test specification and methods by providing a link between requirements and test cases *(1p)*. However, this should not lead to an increase in system complexity *(1p)*. The important relationships between the RE process and the ST process shown in [11] should also be included in the model. In particular, these relationships include data on changes made or to be made to the requirements (0.5p) or test cases (0.5p), comments on the requirements design *(0.5p)*, test results *(1p)*, and information on defects resolved *(0.5p)*.

T_4 (Structured Procedure Concept): In addition to the comprehensive generic system model, the developed approach must include a structured procedure concept *(1p)*. The procedure model should have an iterative periodically recurring form *(1p)* and also represents the time course of system development *(1p)*. This should be cross-lifecycle and include the development steps up to system testing *(1p)*. The procedure concept must also follow the rules of SE and should accordingly be modular and universally applicable *(1p)*. In this way, the procedure model can enable EN a company- and product-specific use of RE methods, as well as the tracing and specification of requirements [10].

T_5 (Model Implementation): As already mentioned, the model should be implemented in a suitable software tool to realize system modeling *(1p)*. The program must visibly and transparently represent the system elements and their interrelationships *(1p)*. In addition, it must have filtering and focusing functions that enable concentration on the essentials or certain elements and thus systematically reduce the complexity of the modeled system *(1p)*. Even more, the software must enable the time-logical arrangement of functions and processes *(1p)* as well as the storage of system states in order to be able to track phases of project management *(1p)*.

T_6 (System Information Integration): The most important system information, which is particularly relevant for tracing the test results and their corresponding product characteristics and requirements, shall be implemented with the model in the program or tracing tool. We have listed some of this information, which is shown in the Figure 2 *(each information 0.5p)*.

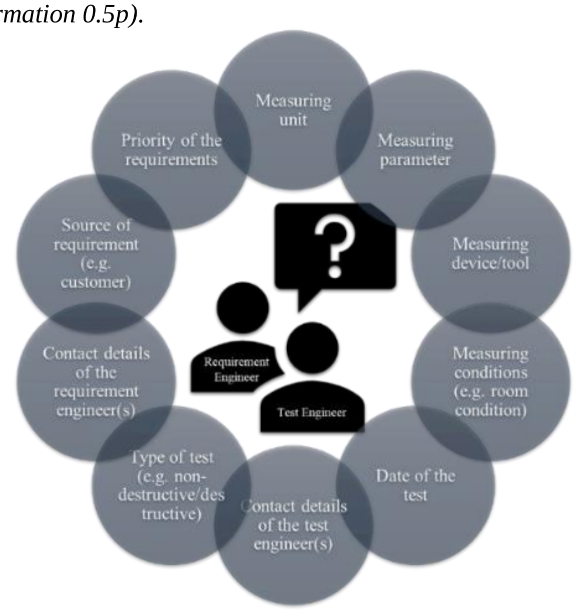

Figure 2. Important information for precise requirements and test engineering.

This information, such as measurement parameters, contact details of the person responsible for the test, the measuring device used, etc., should be accessible in the program at all times. This allows the tracing tool to serve as a means of communication and information exchange for the parties involved in the requirement and the test. These information are to be implemented with the model in a practical program. Depending on the context of use, further information may be required.

III. Results

The results of the evaluation of the research works are listed in relation to their underlying SE approach in Table I. The results of the survey show the lack of a generic, cross-discipline RE approach that considers the linkage of requirements with testing. This problem has been solved in the developed GSE approaches, but the RE methods based on this approach do not consider the integration of inspection characteristics and procedures into the model as well as into the procedure concept. As discussed earlier, the SoSE-based methods seem to have the least ability to fulfil the identified demands, as evidenced by the results of this literature review. In general, the lowest score belonged to T_6 by all three approaches, which addresses the integration of the information listed in Figure 2 into the traceability tool.

TABLE I. EVALUATION OF THE STATE OF THE ART FOR REQUIREMENTS TRACEABILITY METHODS AND THEIR LINKAGE TO TEST CASES.

Evaluation		**Topics**					
Research / Topic		**System Definition and Delimitation**	**System Modeling**	**Integration of Test Cases**	**Structured Procedure Concept**	**Model Implementation**	**System Information Integration**
No.	**Reference**	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**T_6**
MBSE							
1	[73]	4	2	3	3	3	0,5
2	[74]	4	3	3	1	3	1,5
3	[75]	5	3	2	2	3	0
4	[76]	4	3	3	0	3	1
5	[77]	4	3	2	3	3	1
6	[78]	5	3	2	3	3	0
7	[79]	3	2	1	4	5	4
8	[80]	5	3	2	5	4	1
9	[81]	3	2	1	4	5	4
10	[82]	3	3	3	5	3	1
11	[83]	3	2	3	5	2	3
12	[84]	3	3	0	2	3	1
13	[85]	5	3	3	3	2	2,5
14	[86]	4	3	4	1	1	2
15	[87]	3	2	0	0	3	1
16	[88]	5	4	3	4	3	4
17	[89]	2	3	0	1	2	2
18	[90]	2	3	1	1	2	1
19	[91]	5	1	3	3	3	2,5
20	[92]	4	2	0	2	4	0
21	[93]	4	4	4	4	3	5
22	[94]	4	4	4	5	2	4
23	[95]	3	0	0	4	3	1
24	[96]	4	4	3	1	5	1
GSE							
25	[97]	5	5	0	3	4	2
26	[98]	5	5	0	4	4	2
27	[99]	4	5	0	4	4	2
SoSE							
28	[100]	2	2	0	3	3	1
29	[101]	2	2	0	2	3	0,5
30	[102]	2	2	0	3	2	1

The highest score among the MBSE-based methods is achieved by Mandel et al. [93] with 24 scores out of 30, which not only shows a consideration of the system environment and its delineation from the system in the model, but also integrates a lot of information relevant for testing into the implemented model. However, the method does not consider roles. In addition, the procedure model does not fully include the steps for developing and managing the requirements [93]. Second among the highly rated MBSE approaches are the methods of Kremer et al. and Steimer et al., which both achieved a score of 23 out of 30. The presented method of Kremer et al. [88] used an iterative, overarching procedure model. In addition, the use cases and all major system elements are linked in the model. However, different tools were used to link and create the model, resulting in a tool chain in the end. In addition, the information relevant to the test could be more comprehensively included in the tool [88]. The MBSE-based approach of Steimer et al. [94] aims to better integrate production system planning with product development in the early design phases through a model-based planning process. This approach has an iterative V-model as a process concept. The authors pointed out that the method they developed makes models with a larger scale rather confusing. They also mentioned that the mostly abstract graphical representations in SysML, such as rectangles, circles and lines, require expert knowledge for their interpretation [94]. Pessa et al. [80] applied MBSE to an industrial test case to perform the functional design of an innovative control and maintenance system to be integrated into the aircraft fuel system. In their model, the requirements were linked to the use cases, but the system functions were derived directly by inferring the use dependencies between the system and the use case. The model shows the interactions between these elements, but gives no indication of the important data from the test process [80]. Bougain and Gerhard [81] have also developed a product development aid using SysML that helps designers make decisions using examples from previous or similar or other domains, including associated requirements, specifications, use cases, test cases, and other system information [81]. Huth et al. [85] presented an integrated approach that offers the possibilities of model-based requirements and variant modeling. In their work, in addition to test criteria, test cases, features, use cases and stakeholders, they have also linked the goals or targets with the requirements. However, a new sub-model, called the feature model, was created for modeling features, which affects the unified form of the model. In the presented procedure model is also no chronological sequence of the product development process recognizable [85]. The lowest point belongs to the work of Berges et al. [87], where an approach for coupling MBSE and simulation models was presented. The approach, which was exemplarily demonstrated on the development models for the virtual development of wind turbines, has a SysML system model that contains the relevant development information about the wind turbine and is linked to the simulation model in MATLAB Simulink to check the technical solutions for individual functions against the requirements. In this work, the focus is not on the universal representation of the system using the SE approach, but on the linking of the system model with simulation model for the purpose of subsequent automation of change processes [87]. In this approach the test cases are not integrated in the model as well as the methods in [84][92][89][90][95]. Moreover, it can be generally said that all observed MBSE-based methods exhibit high complexity, which complicates the understanding of the system due to the previously mentioned characteristics of MBSE.

The GSE based traceability methods evaluated in Table I offer a generic usability and a universal understanding of the considered systems. In [97], the authors presented an approach based on the e-DeCoDe model for consistent tracking of requirements from complaints. In this way, the identification of failure causes in product development is made possible. As a procedure, the authors developed a four-step process for deriving requirements from complaints. A new RE approach is presented in another work [98] based on e-DeCoDe that supports engineers in R&D Business Networks (BN) in a flexible and customizable way. This approach merges the three dimensions of RE, RM and BN into a structured procedure based on GSE, which enables a high level of understanding of the complex system, for the different partners in the EN. Finally, Bielefeld et al. [99] use the DeCoDe modeling method to analyze fault chains for a complex mechatronic system. In this method, organizational complexity is not considered and the focus is only on the technical complexity of the mentioned system [99].

The use of e-DeCoDe modeling based on the simple matrix format in [97] and [98] facilitates the understanding of the system by defining the essential system artifacts, i.e., requirements, components, functions, processes, and responsible parties. In addition, the interaction between the individual artifacts and the relationship between the system and its environment is captured in these methods. The tool (iQUAVIS) used for the implementation of the RE methods developed by Mistler et al. [97] allows the entire display to be filtered or narrowed to any system element, reducing complexity and providing a better overview of system components [97]. However, none of these approaches, nor any of the SoSE-based approaches explored, consider the linkage of the test methods with the system elements, including the requirements. This also means that the developed procedure concepts, despite their iterative modular structure, lack the relevant development steps for system testing.

IV. CONCLUSION AND FUTURE WORK

In this paper, we have presented the challenges in traceability of requirements and their linkage to test specifications and test methods. According to the studies, existing traceability approaches lack the appropriate methods and tools that offer a cost-quality balance in addition to an even understanding of the system and reduction of complexity.

Based on the aforementioned problem areas, we evaluated the different SE approaches, including specific and universal approaches, in terms of their potential for requirements traceability throughout the product development cycle up to system testing. In this context, the three universal SE approaches, i.e., SoSE, MBSE, and GSE, were presented as the most commonly used solutions for requirements traceability. In a next step, the different traceability methods available in the literature were evaluated through a systematic literature review with respect to their corresponding SE approach.

The results of the literature review show that MBSE enables traceability of requirements and their linkage to system tests, but they have limitations in terms of generic model structure, which limits the equal understanding of the system for the different stakeholders. In addition, some of the developed MBSE methods found in the literature review did not fully consider the important system elements, which should be connected with requirements. Some methods also did not take into account the person view, which enables social level interconnectedness in EN. The developed GSE-based methods that use (e)-/DeCoDe modeling provide a comprehensive view of the key system elements through a simple matrix view that keeps the model complexity low, but none of these methods consider the integration of the test processes into the system model. In addition, the necessary information listed in Figure 2 is not included in the tools used in most of the analyzed works. Compared to the MBSE and GSE approaches, the SoSE-based methods have reached the lowest score with regard to the observed topics.

Based on the identified gaps in the state of the art, we have started to develop an information pool as a data basis for tracing the requirements of a sample product (chemical protective clothing) using the GSE approach. In addition to integrating the system test into an e-DeCoDe model, our database should enable the capture of the system information in a suitable available software tool, e.g., iQUAVIS. Thanks to the integration of the person view in the e-DeCoDe model, this method can lead to a dynamic flow of data and information and an improvement of communication in the multidisciplinary teams. The unified structure of the e-DeCoDe model should allow for a better understanding of the system by different stakeholders without requiring a high level of training, which can be an important factor for SMEs. These benefits can be further explored and evaluated in upcoming research.

REFERENCES

[1] INCOSE, Ed. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities,* 3rd ed., 2006.

[2] N. Schlüter, *Generic Systems Engineering: A Methodical Approach to Complexity Management,* 3rd ed. Berlin: Springer Berlin; Springer Vieweg, 2023.

[3] R. S. Wahono, "Analyzing Requirements Engineering Problems,", *IECI Japan Workshop*, pp. 55–58, 2003. [Online]. Available: https://www.semanticscholar.org/paper/ANALYZING-REQUIREMENTS-ENGINEERING-PROBLEMS-Wahono/b076ea67d29396394ec23a4f38843c740a05d4b0

[4] G. Kotonya and I. Sommerville, *Requirements Engineering: Processes and Techniques,* 1st ed. (Worldwide series in computer science). Chichester: John Wiley & Sons, 1998. [Online]. Available: http://www.loc.gov/catdir/description/wiley031/98016175.html

[5] D. Pandey, U. Suman, and A. K. Ramani, "An Effective Requirement Engineering Process Model for Software Development and Requirements Management," in *Advances in Recent Technologies in Communication and Computing (ARTCom), 2010 International Conference on*, Kottayam, India, 2010, pp. 287–291, doi: 10.1109/ARTCom.2010.24.

[6] I. Gräßler, "A New V-Model for Interdisciplinary Product Engineering,", *Universitätsbibliothek Ilmenau*, 2017. [Online]. Available: https://www.semanticscholar.org/paper/A-new-V-Model-for-interdisciplinary-product-Gr%C3%A4%C3%9Fler/e662dd9ed86b991300dcf715f6935aa267faa3a2

[7] H.-D. Haasis and T. Kriwald, *Knowledge Management in Production and Environmental Protection*. Berlin: Springer Berlin Heidelberg, 2013. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=6438475

[8] T. Pfeifer, Ed. *Knowledge-Based Systems in Quality Assurance: Methods for the Use of Distributed Knowledge* (Quality Management). Berlin, Heidelberg: Springer Berlin Heidelberg, 1996.

[9] J.-P. G. Nicklas, "Approach for a Model-Based Requirements Management for Enterprise Networks," Dissertation, Faculty of Mechanical Engineering and Safety Engineering, University of Wuppertal, Wuppertal, 2015. [Online]. Available: https://www.shaker.de/Online-Gesamtkatalog-Download/2023.01.13-16.39.18-132.195.144.198-rad7F822.tmp/3-8440-4556-2_INH.PDF

[10] N. Schlüter, "Redesign of Requirements Engineering in Networks for Smart Products," in *Potentials of Artificial Intelligence 2020*, Springer Vieweg, Berlin, Heidelberg, 2020, pp. 89–108. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-662-60692-6_6

[11] J. Kukkanen, K. Väkeväinen, M. Kauppinen, and E. Uusitalo, "Applying a Systematic Approach to Link Requirements and Testing: A Case Study," in *2009 16th Asia-Pacific Software Engineering Conference*, Batu Ferringhi, Penang, Malaysia, S. Sulaiman, Ed., 2009, pp. 482–488, doi: 10.1109/APSEC.2009.62.

[12] E. J. Uusitalo, M. Komssi, M. Kauppinen, and A. M. Davis, "Linking Requirements and Testing in Practice,", *2008 16th IEEE International Requirements Engineering Conference*, 2008. [Online]. Available: https://www.academia.edu/15266452/Linking_Requirements_and_Testing_in_Practice

[13] Z. A. Barmi, A. H. Ebrahimi, and R. Feldt, "Alignment of Requirements Specification and Testing: A Systematic Mapping Study," in *2011 IEEE Fourth International Conference on Software Testing, Verification and Validation workshops (ICSTW 2011)*, Berlin, Germany, 2011, pp. 476–485, doi: 10.1109/ICSTW.2011.58.

[14] S. Siegl, K.-S. Hielscher, and R. German, "Model Based Requirements Analysis and Testing of Automotive Systems with Timed Usage Models," in *Requirements Engineering Conference (RE), 2010 18th IEEE International*, Sydney, Australia, 2010, pp. 345–350, doi: 10.1109/RE.2010.49.

[15] S. M. Ooi, R. Lim, and C. C. Lim, "An Integrated System for End-to-End Traceability and Requirements Test Coverage," in *Software Engineering and Service Science (ICSESS), 2014 5th IEEE International Conference on*, Beijing, China, 2014, pp. 45–48, doi: 10.1109/ICSESS.2014.6933511.

[16] B. Ramesh, "Factors Influencing Requirements Traceability Practice,", *Commun. ACM*, 1998. [Online]. Available: https://www.semanticscholar.org/paper/Factors-influencing-requirements-traceability-Ramesh/a09e302f21091e29d62a13f2e81a38fd1df7d505

[17] M. Kolla and M. Banka, "Merging Functional Requirements with Test Cases," Master Thesis, School of Technology - Department of Computer Science, Malmö University, Malmö-Schweden, 2015. [Online]. Available: https://www.semanticscholar.org/paper/Merging-Functional-Requirements-with-Test-Cases-Kolla-Banka/d2d5b7869b87cd1872250d98c1cda805efd2986e

[18] V. Katta and T. Stålhane, "A Conceptual Model of Traceability for Safety Systems," in *Proceedings of the Complex Systems Design & Management Conference*, 2011. [Online]. Available: https://www.academia.edu/19138950/A_Conceptual_Model_of_Traceability_for_Safety_Systems

[19] A. Egyed, S. Biffl, M. Heindl, and P. Grünbacher, "Determining the Cost-Quality Trade-Off for Automated Software Traceability," in *The 20th IEEE/ACM International Conference on Automated Software Engineering : Long Beach, California, USA, November 7-11, 2005*, Long Beach CA USA, D. Redmiles, T. Ellman, and A. Zisman, Eds., 2005, pp. 360–363, doi: 10.1145/1101908.1101970.

[20] D. Graham, "Requirements and Testing: Seven Missing-Link Myths,", *IEEE Softw.*, vol. 19, no. 5, pp. 15–17, 2002, doi: 10.1109/MS.2002.1032845.

[21] F. A. Salim, H. Ali, G. Muller, and K. Falk, "User-centered Data Driven Approach to Enhance Information Exploration, Communication and Traceability in a Complex Systems Engineering Environment," in *MODERN SYSTEMS 2022: International Conference of Modern Systems Engineering Solutions.*, Alan Martin Redmond, Ed., pp. 39–44. [Online]. Available: https://openarchive.usn.no/usn-xmlui/handle/11250/3019183

[22] J. Cleland-Huang, "Just Enough Requirements Traceability," in *Proceedings*, Chicaco, IL, 2006, pp. 41–42, doi: 10.1109/COMPSAC.2006.57.

[23] V. Kirova, N. Kirby, D. Kothari, and G. Childress, "Effective Requirements Traceability: Models, Tools, and Practices,", *Bell Labs Tech. J.*, vol. 12, no. 4, pp. 143–157, 2008, doi: 10.1002/bltj.20272.

[24] S. R. Aleixo, C. Campese, and J. Mascarenhas, "Identification and Classification of Barriers and Benefits of Requirements Traceability in Project Development,", *World J. Adv. Eng. Tech. Sci.*, vol. 4, no. 1, pp. 22–39, 2021, doi: 10.30574/wjaets.2021.4.1.0080.

[25] F. Lin and H. Chen, "Comparative Study of Requirements Traceability in Facing Requirements Change: Systematic Literature Study and Survey,", 2019. [Online]. Available: https://www.diva-portal.org/smash/record.jsf?pid=diva2:1305894

[26] M. Tukur, S. Umar, and J. Hassine, "Requirement Engineering Challenges: A Systematic Mapping Study on the Academic and the Industrial Perspective,", *Arab J Sci Eng*, vol. 46, no. 4, pp. 3723–3748, 2021. doi: 10.1007/s13369-020-05159-1. [Online]. Available: https://link.springer.com/article/10.1007/s13369-020-05159-1

[27] J. A. Estefan, "Survey of Model-Based Systems Engineering (MBSE) Methodologies,", *Incose MBSE Focus Group*, 2007, Art. no. 8. [Online]. Available: https://edisciplinas.usp.br/pluginfile.php/5348231/mod_resource/content/1/mbse_methodology_survey_revb.pdf

[28] T. Weilkiens, *Systems Engineering with SysML/UML: Modeling, Analysis, Design* (The MK/OMG Press). Amsterdam: Morgan Kaufmann, 2011. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=331984

[29] H. Aboutaleb and B. Monsuez, "Towards a Seamless Requirements Management in System Design Using a Higraph-Based Model," in *2016 Annual IEEE Systems Conference (SysCon)*, 2016, doi: 10.1109/syscon.2016.7490663.

[30] G. Sabaliauskaite *et al.*, "Challenges in Aligning Requirements Engineering and Verification in a Large-Scale Industrial Context," in *Requirements Engineering Conference (RE), 2010 18th IEEE International*, Sydney, Australia, 2010, pp. 128–142, doi: 10.1007/978-3-642-14192-8_14.

[31] M. W. Boota, N. Ahmad, and A. H. Masoom, "Requirement Engineering Issues and Their Solutions,", *International Journal of Engineering and Technical Research (IJETR)*, pp. 50–56, 2014.

[32] E. Bjarnason *et al.*, "Challenges and Practices in Aligning Requirements with Verification and Validation: A Case Study of Six Companies,", *Empir Software Eng*, vol. 19, no. 6, pp. 1809–1855, 2014. doi: 10.1007/s10664-013-9263-y. [Online]. Available: https://link.springer.com/article/10.1007/s10664-013-9263-y

[33] P. Mason, "On Traceability for Safety Critical Systems Engineering," in *Software Engineering Conference, 2005. APSEC '05. 12th Asia-Pacific*, Taipei, Taiwan, 2005, 8 pp, doi: 10.1109/APSEC.2005.85.

[34] G. Regan, F. McCaffery, K. McDaid, and D. Flood, "The Barriers to Traceability and their Potential Solutions: Towards a Reference Framework," in *2012 38th Euromicro Conference on Software Engineering and Advanced Applications (SEAA 2012): Cesme, Izmir, Turkey, 5-8 September 2012*, Cesme, Izmir, Turkey, V. Cortellessa, Ed., 2012, pp. 319–322, doi: 10.1109/SEAA.2012.80.

[35] D. Viapiana, G. Riggio, L. Barbieri, and F. Bruno, "An Integrated Approach to Ensure Requirements Traceability During the Product Development Process," in *Design Tools and Methods in Industrial Engineering II*, Rom, Italien, 2022, pp. 328–335, doi: 10.1007/978-3-030-91234-5_33.

[36] R. Wohlrab, E. Knauss, J.-P. Steghöfer, S. Maro, A. Anjorin, and P. Pelliccione, "Collaborative Traceability Management: a Multiple Case Study from the Perspectives of Organization, Process, and Culture,", *Requirements Eng*, vol. 25, no. 1, pp. 21–45, 2020. doi: 10.1007/s00766-018-0306-1. [Online]. Available: https://link.springer.com/article/10.1007/s00766-018-0306-1

[37] J. Krause, A. Kaufmann, and D. Riehle, "The Code System of a Systematic Literature Review on Pre-Requirements Specification Traceability,", 2020, doi: 10.25593/ISSN.2191-5008/CS-2020-02.

[38] F. Stallinger, R. Neumann, Robert Schossleitner, and Stephan Kriener, "Migrating Towards Evolving Software Product Lines: Challenges of an SME in a Core Customer-Driven Industrial Systems engineering context,", 2011. [Online]. Available: https://www.semanticscholar.org/paper/Migrating-towards-evolving-software-product-lines%3A-Stallinger-Neumann/d927e4708f032ee75c5cb7f5be6099f6f5ca4bcc

[39] D. Pérez Ferreira Chaves and T. Peter, *The use of traceability systems in industry - results of a study*. Kassel: Kassel University Press, 2018.

[40] N. Wittine, S. Wenzel, C. Kern, R. Refflinghaus, and T. Trostmann, *Introduction of Traceability into the Continuous Improvement Process of SMEs*. Hannover : publish-Ing, 2020. [Online]. Available: https://www.repo.uni-hannover.de/handle/123456789/9703

[41] C. Schröder, *The Challenges of Industry 4.0 for Small and Medium-Sized Enterprises* (A good society - social democracy #2017 plus). Bonn: Friedrich-Ebert-Stiftung, Division for Economic and Social Policy, 2016.

[42] U. Nikula, J. Sajaniemi, and H. Kälviäinen, "A State-of-the-Practice Survey on Requirements Engineering in Small- and Medium-Sized Enterprises,", Telecom Business Research Center Lappeenranta, Lappeenranta University of Technology, Lappeenranta, Rep. Research Report 1, 2000. [Online]. Available: https://www.semanticscholar.org/paper/A-State-of-the-Practice-Survey-on-Requirements-in-Nikula-Sajaniemi/5f8f57e19c54448eb37f4ff1464c83b74ee4e8b9

[43] United Nations Global Compact, "A Guide to Traceability for SMEs,", United Nations Global Compact, New York, 2016. Accessed: May 2, 2023. [Online]. Available: https://unglobalcompact.org/library/4381

[44] M. Mistler, "Development of a Process Concept for Model-Based Agile Requirements Management (Requirements Engineering and Requirements Management) for Organizations - REMOt," Dissertation, Product Safety and Quality, University of Wuppertal, Wuppertal, 2021.

[45] S. Marchlewitz, J.-P. Nicklas, and P. Winzer, "Using Systems Engineering for Improving Autonomous Robot Performance,", *2015 10th System of Systems Engineering Conference (SoSE)*, 2015. [Online]. Available: https://www.semanticscholar.org/paper/Using-systems-engineering-for-improving-autonomous-Marchlewitz-Nicklas/d54f8a9df40d920941c2e92d9aa401110684adfd

[46] P. Winzer, "Generic System Description and Problem Solving in Systems Engineering,", *IEEE Systems Journal*, vol. 11, no. 4, pp. 2052–2061, 2017, doi: 10.1109/JSYST.2015.2428811.

[47] R. Haberfellner, *Systems Engineering;: Basics and application*, 14th ed. [S.l.]: Orell Füssli Verlag, 2018. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=6795525

[48] A. T. Bahill and B. Gissing, "Re-Evaluating Systems Engineering Concepts Using Systems Thinking,", *IEEE Trans. Syst., Man, Cybern. C*, vol. 28, no. 4, pp. 516–527, 1998, doi: 10.1109/5326.725338.

[49] J.-P. Nicklas, M. Mamrot, P. Winzer, D. Lichte, S. Marchlewitz, and K.-D. Wolf, "Use Case Cased Approach for an Integrated Consideration of Safety and Security Aspects for Smart Home Applications," in *2016 11th System of Systems Engineering Conference (SoSE 2016): Kongsberg, Norway, 12-16 June 2016*, Kongsberg, Norway, 2016, pp. 1–6, doi: 10.1109/SYSOSE.2016.7542908.

[50] M. Jamshidi, "Introduction to System of Systems," in *System of Systems Engineering: Innovations for the 21st century*, M. Jamshidi, Ed., Hoboken, N.J.: Wiley, 2009, pp. 1–20.

[51] A. P. Sage and C. D. Cuppan, "On the Systems Engineering and Management of Systems of Systems and Federations of Systems,", *INFORMATION KNOWLEDGE SYSTEMS Management*, vol. 2, no. 4, pp. 325–345, 2001. [Online]. Available: https://www.deepdyve.com/lp/ios-press/on-the-systems-engineering-and-management-of-systems-of-systems-and-BKxxGlOrUD

[52] A. Gorod, R. Gove, B. Sauser, and J. Boardman, "System of Systems Management: A Network Management Approach," in *2007 IEEE International Conference on System of Systems Engineering: SoSE'07*, San Antonio, TX, USA, 2007, pp. 1–5, doi: 10.1109/SYSOSE.2007.4304218.

[53] A. Gorod, B. Sauser, and J. Boardman, "System-of-Systems Engineering Management: A Review of Modern History and a

Path Forward,", *IEEE Systems Journal*, vol. 2, no. 4, pp. 484–499, 2008, doi: 10.1109/JSYST.2008.2007163.

[54] I. Cherfa, N. Belloir, S. Sadou, R. Fleurquin, and D. Bennouar, "Systems of Systems: From Mission Definition to Architecture Description,", *Syst. Engin.*, vol. 22, no. 6, pp. 437–454, 2019, doi: 10.1002/sys.21523.

[55] INCOSE, Ed. *Systems Engineering Vision 2020* (2.03), 2007.

[56] M. Sollfrank, E. Trunzer, and B. Vogel-Heuser, "Graphical Modeling of Communication Architectures in Network Control Systems with Traceability to Requirements," in *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, Lisbon, Portugal, 2019, pp. 6267–6273, doi: 10.1109/IECON.2019.8927246.

[57] M. Mamrot, S. Marchlewitz, J.-P. Nicklas, and P. Winzer, "Using Systems Engineering for a Requirement-Based Design Support for Autonomous Robots," in *2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2014, doi: 10.1109/smc.2014.6974406.

[58] A. Morkevicius, A. Aleksandraviciene, D. Mazeika, L. Bisikirskiene, and Z. Strolia, "MBSE Grid: A Simplified SysML-Based Approach for Modeling Complex Systems,", *INCOSE International Symposium*, vol. 27, no. 1, pp. 136–150, 2017, doi: 10.1002/j.2334-5837.2017.00350.x.

[59] A. Madni and S. Purohit, "Economic Analysis of Model-Based Systems Engineering,", *Systems*, vol. 7, no. 1, p. 12, 2019. doi: 10.3390/systems7010012. [Online]. Available: https://www.mdpi.com/415220

[60] M. Ryan, S. Cook, and W. Scott, *Application of MBSE to Requirements Engineering-Research Challenges*. University of Wollongong, 2013. [Online]. Available: https://ro.uow.edu.au/eispapers/6335/

[61] A. M. Madni, B. Boehm, R. G. Ghanem, D. Erwin, and M. J. Wheaton, Eds. *Disciplinary Convergence in Systems Engineering Research*, 1st ed. (Springer eBook Collection Engineering). Cham: Springer International Publishing, 2018.

[62] INCOSE, *System Engineering Vision 2035: Engineering Solutions for a Better World*, 2021.

[63] H. Rosenow, "Trade Off Evaluation Methodology for Tool and Method Decisions for Virtualization and Model-Based Development,", Chair of Astronautics, Munich University of Technology, München, 2018. [Online]. Available: https://mediatum.ub.tum.de/1449514

[64] K. G. Young, "Defense Space Application of MBSE - Closing the Culture Chasms," in *SPACE Conferences and Exposition: AIAA SPACE 2015 Conference and Exposition*, Pasadena, California, 2015, doi: 10.2514/6.2015-4620.

[65] A. Albers, R. Dumitrescu, J. Gausemeier, K. Lindow, O. Riedel, and R. Stark, *The Advanced Systems Engineering Strategy: A central Initiative for the Future of Germany as an Engineering and Innovation Hub*. Munich, 2022.

[66] L. Boggero, P. D. Ciampa, and B. Nagel, "An MBSE Architectural Framework for the Agile Definition of System Stakeholders, Needs and Requirements," in *AIAA AVIATION 2021 FORUM*, Reston, Virginia, 2021, doi: 10.2514/6.2021-3076.

[67] P. Winzer and J. Sitte, "Systems Engineering: Old Ideas, New Potential," in *2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583)*, 2004, pp. 2150–2155, doi: 10.1109/icsmc.2004.1400645.

[68] J. Heinke and M. Mistler, "Agile and Model-Based Project Management in Product and Service Development," in *Challenges in Dealing with Requirements in Times of Industrial Change* (Generic Management Reports Band 2019,1), M. Reiche and N. Schlüter, Eds., Düren: Shaker, 2019, pp. 1–26.

[69] P. Winzer, S. Schlund, S. Kulig, and J. Rosendahl, "Methodical Approach for the Development of Networked Mechatronic Systems in Intralogistic Plants According to Requirements," in *Forderungsgerechte Auslegung von intralogistischen Systemen*, H. A. Crostack and M. t. Hompel, Eds., Dortmund: Verl. Praxiswissen, 2007.

[70] M. Mistler, N. Schlüter, and M. Lower, "Analysis of Software Tools for Model-Based Generic Systems Engineering for Organizations Based on e-DeCoDe," in *2021 IEEE International Systems Conference (SysCon)*, Vancouver, BC, Canada, 2021, pp. 1–8, doi: 10.1109/SysCon48628.2021.9447081.

[71] A. Khandoker *et al.*, "Towards a Logical Framework for Ideal MBSE Tool Seselection Based on Discipline Specific Requirements,", *Journal of Systems and Software*, vol. 189, p. 111306, 2022. doi: 10.1016/j.jss.2022.111306. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0164121222000553

[72] J. Ma, G. Wang, J. Lu, H. Vangheluwe, D. Kiritsis, and Y. Yan, "Systematic Literature Review of MBSE Tool-Chains,", *Applied Sciences*, vol. 12, no. 7, p. 3431, 2022, doi: 10.3390/app12073431.

[73] R. Plateaux, O. Penas, S. Mule, P. Hehenberger, S. Patalano, and F. Vitolo, "SCRUM++ Framework Concepts,", *ISSE 2020 - 6th IEEE International Symposium on Systems Engineering, Proceedings*, pp. 1–8, 2020. doi: 10.1109/ISSE49799.2020.9272233. [Online]. Available: https://pure.fh-ooe.at/de/publications/scrum-framework-concepts

[74] J. L. Arockia Irudayaraj, "Functional Driven Product Development Using MBSE," Master´s Thesis, Department of Industrial and Material Science, CHALMERS UNIVERSITY OF TECHNOLOGY, Gothenburg, Sweden, 2020. [Online]. Available: https://odr.chalmers.se/items/d8684009-4e24-4021-ad6e-a063ef87acee

[75] P. Ciampa, B. Nagel, and G. Rocca, "A MBSE Approach to MDAO Systems for the Development of Complex Products,", *AIAA AVIATION 2020 FORUM*, 2020. [Online]. Available: https://www.semanticscholar.org/paper/A-MBSE-Approach-to-MDAO-Systems-for-the-Development-Ciampa-Nagel/e6beeea35d624e95b889230188200ad60e3b2259

[76] Y. Huang, B. Hu, W. Diao, and Z. Xia, "Research on Satellite Modeling and Real-time Simulation Monitoring Based on MBSE," in *2022 2nd Asia-Pacific Conference on Communications Technology and Computer Science: ACCTCS 2022 : proceedings : 25-27 February 2022, Shenyang, China*, Shenyang, China, 2022, pp. 257–262, doi: 10.1109/ACCTCS53867.2022.00060.

[77] S. Gebreyohannes, A. Karimoddini, and A. Homaifar, "Applying Model-Based Systems Engineering to the Development of a Test and Evaluation Tool for Unmanned Autonomous Systems," in *2020 IEEE International Systems Conference (SysCon)*, Montreal, QC, Canada, 2020, pp. 1–7, doi: 10.1109/SysCon47679.2020.9275894.

[78] S. Subarna, A. K. Jawale, A. S. Vidap, S. D. Sadachar, S. Fliginger, and S. Myla, "Using a Model Based Systems Engineering Approach for Aerospace System Requirements Management," in *2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*, San Antonio, TX, USA, 2020, pp. 1–8, doi: 10.1109/DASC50938.2020.9256589.

[79] S. Bougain and D. Gerhard, "Supporting Product Design Decision with a SysML Design History Assistant,", *Procedia CIRP*, vol. 91, pp. 255–260, 2020, doi: 10.1016/j.procir.2020.02.174.

[80] C. Pessa, M. Cifaldi, E. Brusa, D. Ferretto, K. M. Malgieri, and N. Viola, "Integration of Different MBSE Approaches within the Design of a Control Maintenance System Applied to the Aircraft Fuel System," in *2016 IEEE International Symposium on Systems Engineering (ISSE)*, Edinburgh, United Kingdom, 2016, pp. 1–8, doi: 10.1109/SysEng.2016.7753138.

[81] S. Bougain and D. Gerhard, "Integrating Environmental Impacts with SysML in MBSE Methods,", *Procedia CIRP*, vol. 61, pp. 715–720, 2017. doi: 10.1016/j.procir.2016.11.196. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827116313567

[82] J. Marshall, R. Ferguson, D. Matthes, and L. Assadzadeh, "Transitioning Model-Based Systems Engineering to Onboard Spacecraft Electronics," in *2017 IEEE Aerospace Conference : 4-11 March 2017*, Big Sky, MT, USA, M. (. IEEE Aerospace Conference Big Sky, Ed., 2017, pp. 1–15, doi: 10.1109/AERO.2017.7943873.

[83] A.-L. Bruggeman, B. van Manen, T. van der Laan, T. van den Berg, and G. La Rocca, "An MBSE-Based Requirement Verification Framework to Support the MDAO Process," in *AIAA AVIATION 2022 Forum*, Chicago, IL & Virtual, 2022, doi: 10.2514/6.2022-3722.

[84] N. Bursac, "Model Based Systems Engineering to Support Modular Development in the Context of the Early Phase of Product Generation Development," Dissertation, Institute for Product Development (IPEK), Karlsruhe Institute of Technology (KIT), Karlsruhe, 2016. [Online]. Available: https://publikationen.bibliothek.kit.edu/1000054484

[85] T. Huth, D. Inkermann, and T. Vietor, "An Approach for Integrated, Model-based Requirements and Variant Modeling," in *Science Forum: Intelligente Technische Systeme (WInTeSys)*, Paderborn, E. Bodden et al., Eds., 2017, pp. 169–182.

[86] J. Roßmann *et al.*, "Integrated Model-Based System Specification and Simulation: A Case Study of Sensor Design in Space Travel," in *Science Forum: Intelligente Technische Systeme (WInTeSys)*, Paderborn, E. Bodden et al., Eds., 2017, pp. 281–294.

[87] J. M. Berges, J. K. Berroth, Y. Zhang, G. Höpfner, and G. Jacobs, "Networking of Simulation Models and Model-Based Systems Engineering for Virtual Product Development," in *NAFEMS DACH Regionalkonferenz*, Bamberg, Deutschland, 2022, pp. 263–267. [Online]. Available: https://publications.rwth-aachen.de/record/856273

[88] M. Kremer, S. Christiaens, C. Granrath, and M.-A. Meyer, "Scenario and Model-Based Systems Engineering for Highly Automated Driving,", *ATZ Automobiltech Z*, vol. 122, no. 12, pp. 16–21, 2020. doi: 10.1007/s35148-020-0354-y. [Online]. Available: https://link.springer.com/article/10.1007/s35148-020-0354-y

[89] M. Jackson and M. Wilkerson, "MBSE-Driven Visualization of Requirements Allocation and Traceability," in *2016 IEEE Aerospace Conference*, Big Sky, MT, USA, 2016, pp. 1–17, doi: 10.1109/AERO.2016.7500593.

[90] R. Brahmi, I. Belhadj, M. Hammadi, N. Aifaoui, and J.-Y. Choley, "CAD-MBSE Interoperability for the Checking of Design Requirements Based on Assemblability Indicators,", *Applied Sciences*, vol. 12, no. 2, p. 566, 2021. doi: 10.3390/app12020566. [Online]. Available: https://www.mdpi.com/2076-3417/12/2/566

[91] R. Tsui, D. Davis, and J. Sahlin, "Digital Engineering Models of Complex Systems using Model-Based Systems Engineering (MBSE) from Enterprise Architecture (EA) to Systems of Systems (SoS) Architectures & Systems Development Life Cycle (SDLC),", *INCOSE International Symposium*, vol. 28, no. 1, pp. 760–776, 2018, doi: 10.1002/j.2334-5837.2018.00514.x.

[92] J. Suryadevara and S. Tiwari, "Adopting MBSE in Construction Equipment Industry: An Experience Report," in *2018 25th Asia-Pacific Software Engineering Conference (APSEC 2018): Nara, Japan, 4-7 December 2018*, Nara, Japan, 2018, pp. 512–521, doi: 10.1109/APSEC.2018.00066.

[93] C. Mandel, J. Boning, M. Behrendt, and A. Albers, "A Model-Based Systems Engineering Approach to Support Continuous Validation in PGE - Product Generation Engineering," in *2021 IEEE International Symposium on Systems Engineering (ISSE)*, Vienna, Austria, 2021, pp. 1–8, doi: 10.1109/ISSE51541.2021.9582475.

[94] C. Steimer, J. Fischer, and J. C. Aurich, "Model-based Design Process for the Early Phases of Manufacturing System Planning using SysML,", *Procedia CIRP*, vol. 60, pp. 163–168, 2017. doi: 10.1016/j.procir.2017.01.036. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827117300379

[95] M. Lukei, B. Hassan, R. Dumitrescu, T. Sigges, and V. Derksen, "Modular Inspection Equipment Design for Modular Structured Mechatronic Products – Model Based Systems Engineering Approach for an Integrative Product and Production System Development,", *Procedia Technology*, vol. 26, pp. 455–464, 2016. doi: 10.1016/j.protcy.2016.08.058. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212017316304054

[96] E. Windisch, C. Mandel, S. Rapp, N. Bursac, and A. Albers, "Approach for Model-Based Requirements Engineering for the Planning of Engineering Generations in the Agile Development of Mechatronic Systems,", *Procedia CIRP*, vol. 109, pp. 550–555, 2022. doi: 10.1016/j.procir.2022.05.293. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827122007429

[97] M. Mistler, N. Schlueter, M. Loewer, and V. Rafalczyk, "Methodology for a Model-based Traceability of Requirements from Complaints in Business Networks Using e-DeCoDe," in *2021 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, Singapore, Singapore, 2021, pp. 1255–1259, doi: 10.1109/IEEM50564.2021.9673054.

[98] N. Schlüter, M. Mistler, M. Heinrichsmeyer, A. Ansari, and O. Bielefeld, "ReMaiN-Concept for Requirements Management and Engineering in R&D Business Networks in Germany," in *2019 14th Annual Conference System of Systems Engineering (SoSE 2019): Anchorage, Alaska, USA, 19-22 May 2019*, Anchorage, AK, USA, 2019, pp. 308–312, doi: 10.1109/SYSOSE.2019.8753875.

[99] O. Bielefeld, H. Dransfeld, and N. Schlüter, "Development of a Procedure for Analysis of Failure Chains in Complex Mechatronic Systems to Improve Sustainability,", *Procedia Manufacturing*, vol. 21, pp. 870–877, 2018. doi: 10.1016/j.promfg.2018.02.195. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S235197891830235X

[100] Melanie L. Grande, "Modeling Architectures and Parameterization of Spacecraft with Application to Persistent Platforms," Master Thesis, Purdue University, Indiana, USA, 2020. [Online]. Available: https://www.semanticscholar.org/paper/Modeling-Architectures-and-Parameterization-of-with-Grande/03ed84c8a4d5bd388fddac471377c09d60aaae22

[101] L. Knöös Franzén, I. Staack, C. Jouannet, and P. Krus, "An Ontological Approach to System of Systems Engineering in Product Development," in *Proceedings of the 10th Aerospace Technology Congress, October 8-9, 2019, Stockholm, Sweden*, 2019, pp. 35–44, doi: 10.3384/ecp19162004.

[102] W. Power, M. Wylie, P. Mellen, and P. van Bodegom, "A Hybrid between Model-Based Systems Engineering and Agile Methodologies for Simulation of Complex Weapon Systems of Systems," in *2021 IEEE Aerospace Conference (50100)*, Big Sky, MT, USA, 2021, pp. 1–15, doi: 10.1109/AERO50100.2021.9438152.