MBSE WITHIN THE ENGINEERING DESIGN COMMUNITY – AN EXPLORATORY STUDY

Berschik, Markus Christian (1);
Schumacher, Thomas (2);
Laukotka, Fabian Niklas (1);
Krause, Dieter (1);
Inkermann, David (2)

1: Hamburg University of Technology;
2: TU Clausthal

ABSTRACT

Objective of this contribution is to present the use of Model-based Systems Engineering within the engineering design community. Based on a differentiation between SE and MBSE, the definition of three core MBSE elements, namely modelling method, modelling language, and modelling tool as well as the three major aspects of a consistent system model (requirements, behaviour, and structure) a structured review is conducted, focussing on the understanding and motivation as well as the modelling of systems. The review includes 93 publications from Design Society library and proceedings of the CIRP Design conferences during the period from 2011 to 2022. The review points out, that there is an increasing application of MBSE within the engineering design community, mainly focussing on architecture definition or combined engineering activities. Only a small portion of works (16 publications) are providing a consistent approach as these publications link all aspects of the system model and consider all three MBSE elements. It can be concluded, that there is a diffuse understanding of MBSE and different motivations are given to apply more formal system models as well as modelling tools.

Keywords: Systems Engineering (SE), Design engineering, MBSE, Process modelling, Product modelling / models

Contact:
Berschik, Markus Christian
Technische Universität Hamburg
Germany
markus.berschik@tuhh.de

Cite this article: Berschik, M. C., Schumacher, T., Laukotka, F. N., Krause, D., Inkermann, D. (2023) 'MBSE within the Engineering Design Community – An Exploratory Study', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.260

1 INTRODUCTION

Models are central to documenting results, applying simulations, analysing different solutions, and transferring knowledge in different engineering activities. When engineering modern systems involving services and subsystems from various engineering domains different perspectives have to be addressed resulting in a heterogeneous model landscape (Kattner et al. 2019). The different models represent aspects of the system under development and are characterized by diverse presentations and data structures. This leads to challenges when describing the overall system. To integrate the different perspectives and information, there is an increasing body of research focusing on Model-based Systems Engineering (MBSE). MBSE aims to integrate and represent the results of different development activities within one system model (Friedenthal et al. 2015). Existing research points out the current state of practice and applications of MBSE (Huldt and Stenius 2019; Albers and Zingel 2013), the basic benefits and positive attributes of MBSE (Henderson and Salado 2021) or MBSE tool-chains concepts (Ma et al. 2022). Other authors highlight the reduced effort for information transfer between different tasks within the development process (Younse et al. 2021). While these research papers focus on the benefits and challenges of MBSE in practice and industry, there is an increasing body of literature on MBSE within the community of engineering design. Aside from a diffuse understanding, there seem to be different motivations for the use of more formal models to describe the system under development.
The objective of this contribution is to analyse the motivations for applications and research on MBSE as well as the contributions made by authors from the engineering design community. In contrast to existing works, this research aims at revealing insights into how MBSE affects the research in the engineering design community. The overall research question is formulated as *"What are the motivations and fields of applications of MBSE and which contributions are made by authors within the engineering design community?"* This research question is broken down into four study questions focussing on the understanding and motivation of MBSE as well as the modelling of systems. A structured review of 93 papers from the engineering design community is performed, focusing on the understanding and application of the MBSE elements, namely, system model, modelling method, modelling language, and modelling tool. Moreover, the modelled aspects of the system model, namely, requirements, behaviour, and structure are analysed concerning their linkages. The exploratory study reveals the heterogeneity of current research on MBSE and allows to derive fields for further research.

2 SYSTEMS ENGINEERING AND MODEL-BASED SYSTEMS ENGINEERING

In this Section, the link between Systems Engineering (SE) and Model-based Systems Engineering (MBSE) is introduced. To derive the core elements of MBSE the history and established definitions of MBSE are briefly outlined.

2.1 Systems Engineering

SE can be understood as an interdisciplinary approach to the engineering of systems integrating the perspectives of engineering and management and the application of consequent systems thinking. A detailed definition frequently referred to is given by INCOSE, stating "*Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem […]*" (Walden et al. 2015). Further definitions are highlighting different aspects of SE, like processes, lifecycle orientation or validation. The historical development and basic characteristics of SE can be found in e.g. (Hossain et al. 2020). However, the broad and ambiguous understanding of SE leads to slightly different interpretations and practices of SE (Inkermann 2021). Following the understanding of (Haberfellner et al. 2019) and (Walden et al. 2015), SE incorporates consequent *systems thinking* and a *structured procedure* that integrates the different engineering domains. These elements guide the problem-solving process of complex engineering projects, see Figure 1. To support engineers in their work as well as enable effective coordination of the project, *processes*, *methods* and *tools* have to be established (Martin 1997). The processes address the main activities like system requirement definition, architecture definition or verification. Methods define actions to be performed, how to represent information, what information to use as inputs, which tools to use, and how to

https://doi.org/10.1017/pds.2023.260 Published online by Cambridge University Press

decompose tasks and sequence actions. SE is frequently associated with document-based engineering. To overcome the challenges of document-based SE, MBSE shifts the focus to more formal modelling and the integration of different views into a consistent system model.

2.2 Definitions and history of model-based systems engineering

Wymore was one of the first authors to use the term Model-based Systems Engineering (Wymore 1993). To support practical SE, he proposes *system theoretic models* in addition to physics-based engineering models to represent organizational problems. These *system theoretic models* use discrete time automata or state machines and "*are developed, manipulated and managed by system engineers throughout the lifecycle*" (Wymore 1993). These models have to be understood as precursors of today's system models based on SysML, although they were based on mathematical formulas and do not use visual representation. INCOSE seized on the concept and solidified the understanding of SE and MBSE. In 2007 the first definition was published, stating "*MBSE is the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE is part of a long-term trend toward model-centric approaches adopted by other engineering disciplines, including mechanical, electrical, and software.*" (INCOSE 2007) Based on this understanding, MBSE is listed as one of the *cross-cutting systems engineering methods* in the INCOSE Handbook (Walden et al. 2015) which further links MBSE to SE. This linkage is also highlighted by (Friedenthal et al. 2015) stating "*MBSE emphasizes the use of models to perform systems engineering activities that are traditionally performed using documents*". Other definitions agree, that MBSE is a specific type of SE (Weilkiens 2022) and is based on the application of formalized representations (models) of systems to support and facilitate the performance of SE tasks (Singam 2022). To border MBSE, it is not understood as applying modelling to any (engineering) process but the explicit support of SE activities as for instance defined by (INCOSE 2007) and (ISO/IEC/IEEE 2015) as well as using semiformal system modelling techniques. Thus, the use of the term Systems Engineering is important in this context. The translation into other languages comes with the risk of losing the real meaning of Systems Engineering and its holistic approach and activities (Alt 2012). The tools for implementing MBSE have evolved from mathematically based descriptions to system models created with dedicated authoring tools and modelling languages that represent the formalized information graphically like SysML.

2.3 Elements of model-based systems engineering

MBSE claims that the results of different SE activities are integrated into a consistent system model (Friedenthal et al. 2015). Thus, the system model is developed simultaneously with the system under development during the problem-solving process, see the lower part of Figure 1.

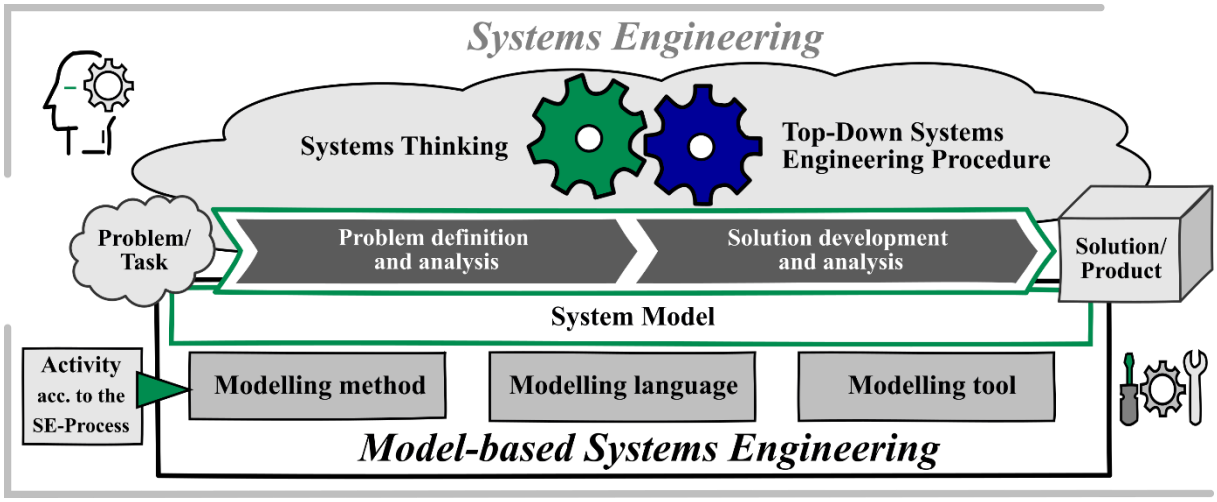

Figure 1: Basic concept of systems engineering and model-based systems engineering.

This system model integrates different views of the system, namely *requirements*, *behaviour*, *structure* and *parameter* (Friedenthal et al. 2015) and is structured into a problem and solution space. To develop a system model three elements are essential: a *modelling method*, a *modelling language* and a *modelling*

https://doi.org/10.1017/pds.2023.260 Published online by Cambridge University Press

tool (Delligatti 2014). These three elements complemented by the system model itself can be considered as the four crucial MBSE elements, as presented in Figure 1 and introduced in the following sections.

System Model in Model-based Systems Engineering

A system model is a cross-linked set of model elements (Friedenthal et al. 2015). The single model elements are heterogeneous since they are representing different system aspects, like requirements, behaviour, structure or parameters that are used to represent the system under development. Based on these aspects a system model links model elements representing, for instance, architecture descriptions, interface descriptions, design constraints, test cases as well as relations between them. For appropriate handling and visualisation of the system model applications of the different system views are established (ISO/IEC/IEEE 2015; Weilkiens 2007; Alt 2012). While these model elements and their relationships, in general, correspond to views that are established in engineering design theories, like the function-behaviour-structure framework proposed by (Gero and Kannengiesser 2004), MBSE targets a more formal approach to that concept. The different views of the system model enable the analysis of selected model elements, e.g., a traceability view, which presents all existing relations between specified model elements. To visualise system views within MBSE different diagram types are usually used.

Modelling Methods in Model-based Systems Engineering

The system model evolves out of different SE activities performed by different engineering teams. To create a consistent system model, modelling methods provide guidance by defining *what* has to be modelled, *when* and *how* in the process. Modelling without a defined modelling method results in a wide model variance (Delligatti 2014) which impedes a coherent system model. Therefore, a modelling method defines the purpose and scope of modelling (Delligatti 2014) for each activity according to the SE process. The acceptance of MBSE in the industry strongly depends on the selected modelling method (Saqui-Sannes et al. 2022). In literature, different modelling methods are proposed like INCOSE Object-Oriented Systems Engineering Method (OOSEM) (Friedenthal et al. 2015) or the System Modelling method (SYSMOD) (Weilkiens 2007) which are associated with SysML. Another modelling method, not using SysML is for instance CONSENS (Gausemeier et al. 2014).

Modelling Languages in Model-based Systems Engineering

The generation of models requires a modelling language defining the modelling elements available (syntax) and their semantics and thus leading to a standardized medium for communication and information sharing. The language defines the elements, and types of relationships and in the case of a graphical modelling language the notations for visualizing the elements and relationships on diagrams (Delligatti 2014). Within MBSE the use of the semiformal Systems Modelling Language (SysML) is established but there are also other modelling languages like UML (Weilkiens 2007), OPM (Dori 2011) or MARTE (Gérard et al. 2010).

Modelling Tool in Model-based Systems Engineering

Modelling tools are a special kind of authoring software incorporating the rules for modelling and visualization based on modelling languages to create and manipulate the underlying data model (Delligatti 2014). This data model leads to an immediate synchronization of all diagrams within the system model. Different tools like Cameo Systems Modeler, Enterprise Architect, Rhapsody or Papyrus are applied in research and industry. These tools provide different functions like generation of system views, linkage of model elements, automated traceability presentation, simulation and formal verification of created diagrams to check against errors or inconsistencies (Saqui-Sannes et al. 2022).

It can be concluded, that all mentioned elements (*system model, modelling method, modelling language* and *modelling tool*) are required for the appropriate application of MBSE.

3 MBSE WITHIN THE ENGINEERING DESIGN COMMUNITY

To explore the current state of research and application of the term MBSE in general, concerning the identified MBSE elements in addition to their application purposes, a structured literature review was conducted. This structured review is derived from the systematic review process PRISMA (Moher et al. 2009). Results presented in the following sections give insights into the understanding of MBSE, the purpose of MBSE, as well as methods and languages, frequently used within the engineering design community. The structured review focuses on the four study questions derived from the overall research question (see Section 1) of this paper and is depicted in Figure 2. These questions can be differentiated into two groups. SQ1 and SQ2 are focused on the understanding and motivation of using MBSE in the engineering design community. SQ3 and SQ4 are focussing on the system modelling itself.

https://doi.org/10.1017/pds.2023.260 Published online by Cambridge University Press

Understanding and Motivation of MBSE	Modelling of Systems
SQ1: What is the motivation and contribution to using MBSE? **SQ2:** Which modelling-elements (modelling languages, modelling methods and modelling tools) are the focus of current research?	**SQ3:** What is the purpose of modelling reported in the publications and which application is considered? **SQ4:** Which aspects of the system model are considered and how are they connected?

Figure 2: Overview of study questions.

3.1 Literature review procedure

The procedure of the literature review is illustrated in Figure 3. To establish a first dataset, 93 publications were considered, gathered from the Design Society library (57 papers) and the proceedings of the CIRP Design conferences (36 papers). These conferences are assumed to give a comprehensive insight into the engineering design community and are, thus, representative of the current research. The publications were identified based on the term Model-based Systems Engineering, similar spellings or their abbreviation (MBSE) that are used in the title, abstract, or keywords. The search covers the period from 2007 when the first version of SysML was published by OMG until today. However, the first publications found only date back to 2011. Before starting the analysis, categories and parameters for the review are derived reflecting the defined study questions, the MBSE elements and aspects of system models, see Section 2.3. The categories were tested and refined by a pre-analysis including 36 publications. This pre-analysis was conducted as a peer- review of two authors and a detailed discussion to assure a consistent understanding of the categories. A major point, besides the area of application, is the usage of the previously presented commonly established elements of MBSE. It is distinguished, whether the paper presented a new method or the presented approach is incorporated into already established methods. Explicit specifications of the tool and language are investigated.
Regarding the system model, it is distinguished whether requirements, structure and/or behaviour are modelled. As a fundamental goal of the system model, the linkage between the different aspects was analysed. Regarding the complete publication, it is determined how the authors of the respective/reviewed publication describe their approach. In addition, meta-information such as the use of MBSE and its different others forms of writing in the title, abstract, and keywords are analysed.

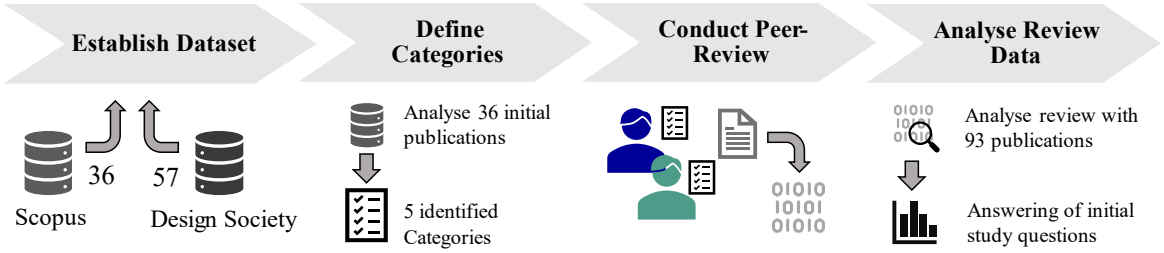

Figure 3: Steps, inputs and results of the structured literature review.

To distinguish the publications, a categorisation is derived based on the first 36 publications. Five categories namely *benefits MBSE*, *benefits SysML*, *application MBSE*, *application SysML* and *other* are identified. This classification is based on the description in the publication and thus the assessment of the respective authors and does not correlate with the described aspects of MBSE. The primary difference between works describing benefits versus applications is the final implementation of the modelling in the paper. *Benefits MBSE* thus describes the benefits of MBSE but does not build any modelling on them. It remains only an approach and a statement of the possible positive benefits. The same applies to papers that describe the benefits of modelling with SysML but do not show any modelling. These publications do not allow for further analysis regarding the modelling aspects. Additionally, the distinction between SysML and MBSE is made based on the described scope of the publication, which refers either to the modelling language SysML or to the field of MBSE. The category *other* is used for unclassifiable publications. Building on the presented categories, the review is conducted using a double review with a control loop afterwards. The results[1] are analysed regarding the given study questions, but also looking for saliences in the data and are presented in the next section.

1 For the complete dataset, including references and review, check the complementary DOI: 10.15480/336.4976

https://doi.org/10.1017/pds.2023.260 Published online by Cambridge University Press

3.2 Review results

Based on the analysed data set of 93 publications, the question given in Figure 2 are answered and the findings are presented in the following.

3.2.1 Understanding of MBSE and motivation to use MBSE

To analyse the current heterogeneity of the current understanding of MBSE within the engineering design community and motivations to use elements of MBSE, two research questions were answered.

SQ1: What is the motivation and contribution to using MBSE?

The usage of the term MBSE in the analysed publications is distinguished based on five types, naming the motivation or application of MBSE for the research. Figure 3 presents the evolution of motivation and applications. Thus, the number of papers is continuously increasing over the review period. Publications describing the benefits of SysML and MBSE present a minority of current research. Since the ratio of application-oriented publications and those reporting benefits is decreasing, it can be concluded that in the community MBSE is used for concrete tasks within research.

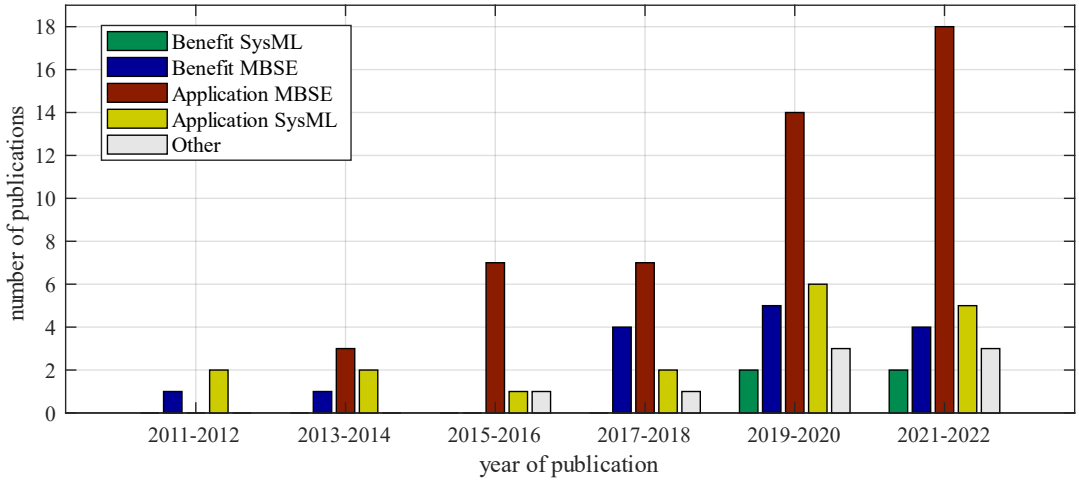

Figure 3: Chronological evolution of the number of publications and their distribution with their classification (n=93).

SQ2: Which modelling-elements (modelling languages, modelling methods and modelling tools) are the focus of current research?

Since MBSE comprises different elements that have to be addressed to cope with different SE activities, see Section 2.3, it was analysed how these three elements are addressed in the publications. Figure 4 illustrates the usage of methods and languages, as well as the changes within the period, analysed. The number of own custom methods described and modelled is increasing in the period considered. 59% of the reviewed publications describe and present their own custom modelling methods, while 23% allocate their contribution to an established method. Focusing on the 22 papers using established modelling methods, there is no predominantly used method. Four papers refer to the RFLP-framework, which, thus, is the most often used framework for modelling. The usage of SysML is increasing over the considered period and appears to be the most often used modelling language with 64 % in all publications. Here, it was also analysed whether the standard set of SysML elements or adaptions of these were used in the papers. Adaptions of SysML are given, if custom elements or new stereotypes were used, to cope with author-specific applications. CONSENS was the second most often used language (8%), while 11% of the papers analysed used a different language like graphs and 16% did not explicitly state which modelling language was used. The modelling tool is only explicitly specified in 36% of the publications with NoMagic's Cameo Systems Modeler being used in 18% and all other explicitly named tools occurring in the other 18% of the papers. With 64%, the majority of papers do not state what tools were used. Based on the results it could often be implied, that a certain tool was used, however, if not explicitly stated these papers were categorized as not specified. Among all the papers, at least one of the elements is described.

https://doi.org/10.1017/pds.2023.260 Published online by Cambridge University Press

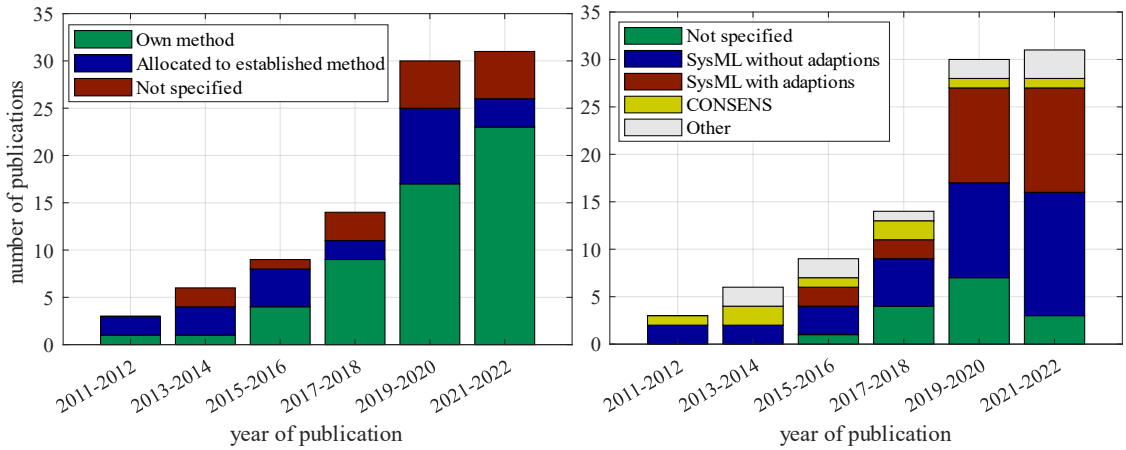

Figure 4: Distribution of methods on the left and languages on the right (n=93).

3.2.2 System model and purposes of modelling

The purpose of MBSE is to generate a consistent system model including information and results from different engineering domains and activities. To analyse the purpose of modelling and identify the different aspects of the system model, two study questions were answered.

SQ3: What is the purpose of modelling reported in the publications and which application is considered?

All publications presenting MBSE or SysML applications (56 publications) were investigated concerning the modelling purpose and fields of applications. Based on the content each paper was categorized into 15 SE application areas like *architecture definition*, *requirements engineering* or *knowledge management*, see Figure 5. The basis for the derived activities is the system life cycle processes based on the ISO 15288 (ISO/IEC/IEEE 2015). For publications which could not be allocated to one of the SE processes individual categories were defined, like the *linkage of system and production*, which is representing the interactions between system development and production.

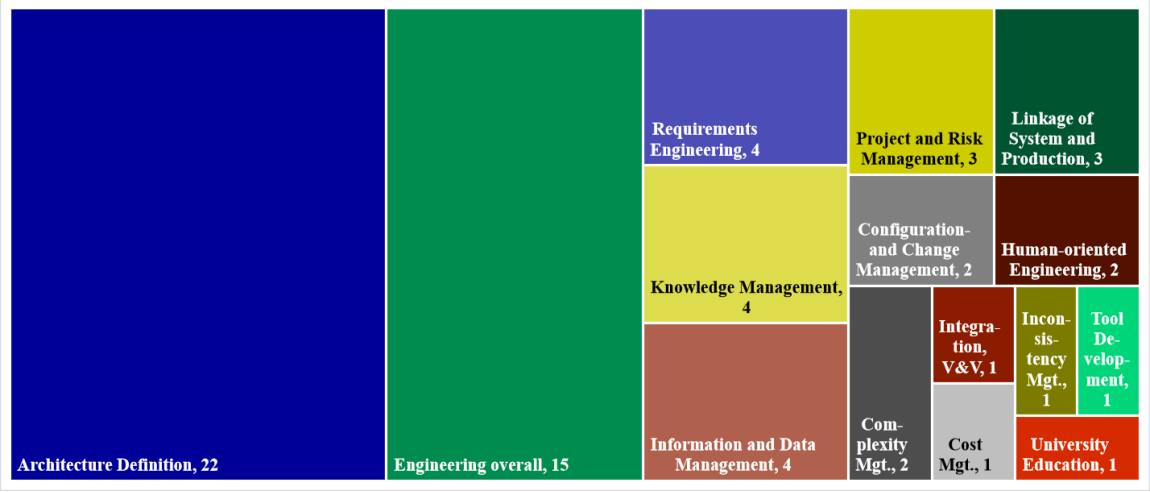

Figure 5: Modelling purposes categorized into 15 application areas (n=56).

A more comprehensive investigation of the modelling purposes shows that 67% of the papers apply MBSE or SysML to support technical SE activities like (Paetzold and Kößler 2014) while 26% support SE management activities like (Meißner et al. 2021). Within the technical SE activities, *architecture definition* was most commonly supported by the application of models, e.g. (Hanna et al. 2021). The most considered management-oriented SE activities are *knowledge management* and *information and data management, e.g. (*Katzwinkel and Löwer 2019*)*. Publications considering more than one SE task were classified as *engineering overall*. An example is given by (Bougain and Gerhard 2018), addressing requirements and design definitions based on environmental impacts for general product development tasks or eco-design. An exemplary publication which is representing the category of requirements engineering is (Inkermann et al. 2019).

https://doi.org/10.1017/pds.2023.260 Published online by Cambridge University Press

SQ4: Which aspects of the system model are considered and how are they connected?
Focusing on the aspects of the system model addressed in the publications, it can be concluded that in 58 out of 93, the structure of a system is modelled, while the behaviour is modelled in 47 out of 93, and requirements are modelled in 45 out of 93 publications. In 25% of the publications, no aspect of the system model is modelled.

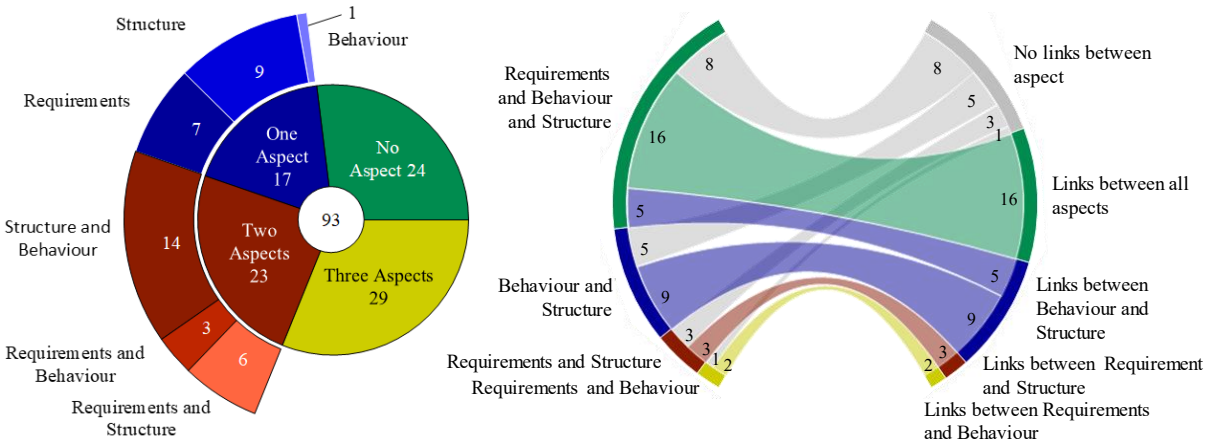

Figure 7a: Modelling of aspects of the system model (n=93), 7b: Modelled linkages between the different aspects of the system model (n= 52).

Figure 7a represents the number of system model aspects modelled in the publications, inner ring. The results indicate, that in 29 publications all three aspects are addressed, while the focus is on the modelling of behaviour and structure for those who model two aspects (14 publications). As described in Section 2.3, the value of the model-based approaches is achieved by linking the different aspects within the system model. Analysing the publications that model at least two aspects (52 papers), in 35 works the different aspects are linked to each other. While in 29 publications all three aspects are modelled, only in 21 publications at least two aspects of the system model are linked, see Figure 7b. It can be seen that in 16 of these publications, all aspects are linked. Hence, only 16 of 94 publications (17%) show a consistent approach according to the elements of MBSE and aspects of the system model described in Sections 2.3. Also, half of these publications state that their approach is MBSE.

3.3 Discussion and conclusions of the review

The presented structured review provides insights into the understanding, application, and implementation of MBSE within the engineering design community in the period from 2011 to 2022. To remain as objective as possible, ambiguous content or complementary work by authors that was not explicitly included or referenced in the paper has been excluded. Based on the findings of the review the following conclusions on the understanding, application and implementation of MBSE can be drawn:

- The relevance of MBSE is rising within the engineering design community, as can be seen by the increasing numbers of publications, especially those focusing on implementations and application of modelling approaches. The usage of the defined elements of MBSE within the papers differs greatly. In many publications, not all elements or aspects are considered or specified at all.
- There is a range of applications, which results in multiple and diverse usages of the wording of MBSE. The different applications of MBSE result in a multitude of newly presented (modelling) methods focusing for instance on modular lightweight design or requirements engineering. Concurrently, there are references to existing and established methods. A ubiquitous method, a majority of papers are referencing, could not be identified.
- SysML, with and without adaptions, could be identified as the predominantly used modelling language. The modelling tool is rarely named explicitly. However, when named, the Cameo Systems Modeler is used most often. Regarding the system model, especially the aspects of requirements, structure and behaviour as well as their linkage differs greatly. About a quarter of all publications present no modelling at all. In most of the other papers, the structure is modelled. Only in 16 of all publications all three aspects are modelled and linked. It can be noted that the

https://doi.org/10.1017/pds.2023.260 Published online by Cambridge University Press

linkage of the different system model aspects is often not apparent from the description in the publication and therefore lack the benefits of the usage of a consistent system model as a fundamental objective of MBSE.

Besides the publications describing the application of MBSE, there are several publications explicitly describing the application of SysML. These publications often utilize the term MBSE to establish the benefits of modelling and the modelling language SysML before transferring it into applications like the impact analysis of structural dynamics (Jagla et al. 2021) or the data handling of product development methods like the modular lightweight design (Hanna et al. 2021).

4 SUMMARY AND OUTLOOK

This paper presents a structured review of motivations, applications and contributions made within the field of MBSE by authors from the engineering design community based on a manageable subset originating from two representative pools of publications. It was found that there is a high number of research papers pointing out the benefits of MBSE or SysML without providing insights on specific applications and modelling. The major part of these works uses MBSE for architecture definition. It was observed that most of the current works propose their own custom methods for modelling and do not refer to existing ones. At the same time, only a small portion (16 publications out of 93) is providing a consistent approach according to the MBSE elements and aspects of the system model. These publications link all aspects of the system model. In addition, in most of the publications, SysML is used without adaptions. Overall, it can be concluded, that the more formal modelling using SysML as well as the possibility to link the different views upon a system is the main motivation for applying MBSE or SysML within the engineering design community. However, it is important to notice, that there is an increasing number of modelling methods developed instead of applying established methods. Taking into account that there is a diverse understanding of the term MBSE it is hard to point out the research contributions made by the papers analysed. Most of the works report applications or even only refer to the benefits without providing insights on the modelling like language and linking of system model aspects. Only in some works (26 out of 93 publications) adaptions of SysML are introduced, which can be seen as a contribution. It is important to mention, that this exploratory study does not allow drawing detailed conclusions on the modelling method and their theoretical basis in the sense of engineering design theories. The link between MBSE, in particular the modelling method, and existing theories in engineering design thus will be part of future research. The long-term goal is to link existing theories, like the function-behaviour-structure framework (Gero and Kannengiesser 2004) and the more formal modelling methods introduced in the field of MBSE. Another focus of future research will be on linking cross-domain and domain-specific models, both from a methodological and data model perspective. As also shown by the many approaches in the literature that target applications outside of classical systems engineering tasks, the benefits of using system models are applicable in an increasing number of domains. When entering these fields, a clear understanding and use of terminology is becoming increasingly important. The authors are contributing to a more consistent understanding of the term MBSE as well as the motivations associated with the use of single elements like the language by referring to the presented core elements of MBSE and the link between SE and MBSE.

REFERENCES

Albers, A.; Zingel, C. (2013): Challenges of Model-Based Systems Engineering: A Study towards Unified Term Understanding and the State of Usage of SysML. In Abramovici, M.; Stark, R. (Eds.): Smart Product Engineering. Berlin, Heidelberg: Springer Berlin Heidelberg , pp. 83–92.

Alt, O. (2012): Modellbasierte Systementwicklung mit SysML. München: Hanser.

Bougain, S.J.; Gerhard, D. (2018): A CBR APPROACH FOR SUPPORTING ECODESIGN WITH SYSML. In Maier, A.; Kim, H.; Oehmen, J.; Salustri, F.; Škec, S.; Kokkolaras, M. (Eds.): Product, services and systems design. Red Hook, NY: Curran Associates Inc (DS, 87, 3).

Delligatti, L. (2014): SysML Distilled. A Brief Guide to the Systems Modeling Language: Addison-Wesley.

Dori, D. (2011): Object-Process Methodology. In Schwartz, D.; Te'eni, D. (Eds.): Encyclopedia of Knowledge Management, Second Edition: IGI Global, pp. 1208–1220.

Friedenthal, S.; Moore, A.; Steiner, R. (2015): A Practical Guide to SysML. The Systems Modeling Language. 3rd ed.: Elsevier.

Gausemeier, J.; Rammig, F.J.; Schäfer, W.; Sextro, W. (Eds.) (2014): Dependability of Self-Optimizing Mechatronic Systems. Berlin, Heidelberg: Springer Berlin Heidelberg.

https://doi.org/10.1017/pds.2023.260 Published online by Cambridge University Press

Gérard, S.; Espinoza, H.; Terrier, F.; Selic, B. (2010): 6 Modeling Languages for Real-Time and Embedded Systems. In Giese, H.; Karsai, G.; Lee, E.; Rumpe, B.; Schätz, B. (Eds.): Model-Based Engineering of Embedded Real-Time Systems, vol. 6100. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 129–154.
Gero, J.S.; Kannengiesser, U. (2004): The situated function–behaviour–structure framework. In Design Studies 25 (4), pp. 373–391. http://doi.org/10.1016/j.destud.2003.10.010.
Haberfellner, R.; Weck, O. de; Fricke, E.; Vössner, S. (2019): Systems Engineering. Cham: Springer International.
Hanna, M.; Schwenke, J.; Schwede, L.-N.; Laukotka, F.; Krause, D. (2021): Model-based application of the methodical process for modular lightweight design of aircraft cabins. In Procedia CIRP 100, pp. 637–642. http://doi.org/10.1016/j.procir.2021.05.136.
Henderson, K.; Salado, A. (2021): Value and benefits of model-based systems engineering (MBSE): Evidence from the literature. In Syst Eng 24 (1), pp. 51–66. http://doi.org/10.1002/sys.21566.
Hossain, N.U.; Jaradat, R.M.; Hamilton, M.A.; Keating, C.B.; Goerger, S.R. (2020): A Historical Perspective on Development of Systems Engineering Discipline: A Review and Analysis. In J. Syst. Sci. Syst. Eng. 29 (1), pp. 1–35. http://doi.org/10.1007/s11518-019-5440-x.
Huldt, T.; Stenius, I. (2019): State-of-practice survey of model-based systems engineering. In Syst Eng 22 (2), pp. 134–145. http://doi.org/10.1002/sys.21466.
INCOSE (Ed.) (2007): INCOSE Systems Engineering Vision 2020. INCOSE - Technical Operations (INCOSE-TP-2004-004-02). Available online at https://sdincose.org/wp-content/uploads/2011/12/SEVision2020_2007 1003_v2_03.pdf.
Inkermann, D. (2021): SHAPING METHOD ECOSYSTEMS - STRUCTURED IMPLEMENTATION OF SYSTEMS ENGINEERING IN INDUSTRIAL PRACTICE. In Proc. Des. Soc. 1, pp. 2641–2650. http://doi.org/10.1017/pds.2021.525.
Inkermann, D.; Huth, T.; Vietor, T.; Grewe, A.; Knieke, C.; Rausch, A. (2019): Model-Based Requirement Engineering to Support Development of Complex Systems. In Procedia CIRP 84, pp. 239–244. http://doi.org/10.1016/j.procir.2019.04.345.
ISO/IEC/IEEE (2015): ISO/IEC/IEEE International Standard - Systems and software engineering -- System life cycle processes. ISO 15288. Piscataway, NJ, USA: IEEE, 2015.
Jagla, P.; Jacobs, G.; Siebrecht, J.; Wischmann, S.; Sprehe, J. (2021): Using SysML to Support Impact Analysis on Structural Dynamics Simulation Models. In Procedia CIRP 100, pp. 91–96. http://doi.org/10.1016/j.procir.2021.05.015.
Kattner, N.; Bauer, H.; Basirati, M.R.; Zou, M.; Brandl, F.; Vogel-Heuser, B. et al. (2019): Inconsistency Management in Heterogeneous Models - An Approach for the Identification of Model Dependencies and Potential Inconsistencies. In Proc. Int. Conf. Eng. Des. 1 (1), pp. 3661–3670.
Katzwinkel, T.; Löwer, M. (2019): MBSE-integrated Parametric Working Surfaces as part of a PLM Design Approach. In Proc. Int. Conf. Eng. Des. 1 (1), pp. 3671–3680. http://doi.org/10.1017/dsi.2019.374.
Ma, J.; Wang, G.; Lu, J.; Vangheluwe, H.; Kiritsis, D.; Yan, Y. (2022): Systematic Literature Review of MBSE Tool-Chains. In Applied Sciences 12 (7), p. 3431. http://doi.org/10.3390/app12073431.
Martin, J.N. (1997): Systems Engineering Guidebook: CRC Press.
Meißner, M.; Jacobs, G.; Jagla, P.; Sprehe, J. (2021): Model based systems engineering as enabler for rapid engineering change management. In Procedia CIRP, pp. 61–66. http://doi.org/10.1016/j.procir.2021.05.010.
Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. (2009): Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. In BMJ (Cl. research ed.) 339. http://doi.org/10.1136/bmj.b2535.
Paetzold, K.; Kößler, J. (2014): A SYSTEM INTEGRATION METHOD FOR THE CONTINUOUS SUPPORT OF THE DESIGN PROCESS. In : Proceedings of the DESIGN 2014 13th International Design Conference.
Saqui-Sannes, P. de; Vingerhoeds, R.A.; Garion, C.; Thirioux, X. (2022): A Taxonomy of MBSE Approaches by Languages, Tools and Methods. In IEEE Access 10, pp. 120936–120950. http://doi.org/10.1109/ACCESS. 2022.3222387.
Singam, C.; (2022): Model-Based Systems Engineering (MBSE). SEBoK Wiki: Guide to the Systems Engineering Body of Knowledge. SEBoK v. 2.6. Edited by San Diego, CA: International Council on Systems Engineering (INCOSE). 20.05.2022. Available online at https://www.sebokwiki.org/wiki/Model-Based_Systems_Engineering_(MBSE) (accessed 17.10.2022).
Walden, D.D.; Roedler, G.J.; Forsberg, K.; Hamelin, R.D.; Shortell, T.M. (Eds.) (2015): Systems engineering handbook. A guide for system life cycle processes and activities; INCOSE-TP-2003-002-04, 2015. International Council on Systems Engineering. 4. edition. Hoboken, NJ: Wiley.
Weilkiens, T. (2007): Systems engineering with SysML/UML. Modeling, analysis, design. Amsterdam, Boston, Heidelberg, London: Elsevier Morgan Kaufmann OMG Press (OMG Press series).
Weilkiens, T. (2022): Definition of MBSE Revised. Edited by Tim Weilkiens. Available online at https://mbse4u.com/2022/01/11/definition-of-mbse-revised/ (accessed 03.10.2022).
Wymore, A.W. (1993): Model-Based Systems Engineering: CRC Press.
Younse, P.J.; Cameron, J.E.; Bradley, T.H. (2021): Comparative Analysis of Model-Based and Traditional Systems Engineering Approaches for Architecting a Robotic Space System Through Automatic Information Transfer. In IEEE Access 9, pp. 107476–107492. http://doi.org/10.1109/ACCESS.2021.3096468.