Digital Engineering 4 (2025) 100037

Contents lists available at ScienceDirect

Digital Engineering

journal homepage: www.sciencedirect.com/journal/digital-engineering

Review

SysML process chains in MBSE: Systematic literature review and future research directions

Thomas Schumacher [a,*], Chris-Kilian Müller [a,b], David Inkermann [a]

[a] Institute of Mechanical Engineering, TU Clausthal, Clausthal-Zellerfeld, Germany
[b] IAV GmbH, Berlin, Germany

ARTICLE INFO

Keywords:
Process chains
Model Transformation
Systematic Literature Review
Model-based Systems Engineering
Digital Engineering

ABSTRACT

Effective engineering process involving different engineering domains requires the linking of various engineering processes. This linkage must consider procedural, data interchange and organisational aspects and is referred to as a *process chain*. This article presents the results of a systematic literature review, to analyse existing process chains that are used to perform Model-based Systems Engineering activities. This process chain contains SysML models and is characterised by different purposes and implementations. In the systematic literature review, 412 publications are considered and 43 publications are analysed in detail. The results of this analysis indicate that in most process chains SysML models serve as source models to generate different types of simulation models. Here, structural and behavioural aspects of the SysML models are reused to support engineering tasks in architecture definition as well as verification and validation. Moreover, the in-depth analysis of the implementations indicates that application-specific interfaces are used to transform model information within the process chains. Leveraging on the executed literature study and the properties of process chains, this paper introduces an initial framework for developing SysML process chains and presents an exemplary application considering a process chain connecting SysML and CAD models.

1. Introduction

Engineering of modern technical systems requires the close collaboration of stakeholders from different engineering domains. Systems failures often result from insufficient communication between stakeholders and outdated, incomplete, or inconsistent requirements and specifications. These problems are exacerbated by document-based approaches to Systems Engineering with its point-to-point communication channels and missing mechanisms to enforce consistency or completeness between engineering artefacts and models. Following the basic principles of Systems Engineering [1], Model-based Systems Engineering (MBSE) contributes to improve the collaboration of different engineering domains by establishing a comprehensive system model as a central data repository [2,3]. Semi-formal modelling languages like SysML define the syntax and semantics of each model element [4] and foster collaboration and a common understanding of the evolving system [2,5]. While the application of MBSE is increasing across industries [6] and research, it is common sense that main improvements regarding quality and efficiency can be achieved in earlier parts of Systems Engineering focussing on system architecting and design, requirements analysis, and traceability between system requirements and the realisation. For example, SysML-models, being a de facto standard within MBSE [7,8] can be applied to define the system structure and behaviour as well as the overall parameters of the system under development. However, these models do not replace domain-specific models like CAD models in the downstream process. These are necessary to define, e.g. the concrete geometry and spatial arrangement of components, analyse and evaluate potential disruptive effects, such as temperature influences [9], and drive simulations. It becomes clear that models created as part of MBSE have to be linked to domain-specific engineering models as these focus on more specific aspects like geometry, manufacturability, thermodynamics or control of subsystems. The different models relate to each other because they describe the same system from different viewpoints and build on the results of the previously developed model. This results in the question of how to link the different models needed to support the entire engineering process. Development and handling of the different models involves various activities and computer tools and thus can be considered as a process chain [10]. These process chains

* Corresponding author.
E-mail addresses: schumacher@imw.tu-clausthal.de (T. Schumacher), chris-kilian.mueller@iav.de (C.-K. Müller), inkermann@imw.tu-clausthal.de (D. Inkermann).

https://doi.org/10.1016/j.dte.2025.100037
Received 29 October 2024; Received in revised form 12 January 2025; Accepted 20 February 2025
Available online 27 February 2025
2950-550X/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

include different modelling and programming methods to create, complete or transform digital models to support visualisation, documentation, simulation, optimisation or control data [11]. This paper focuses on *SysML process chains.* These SysML process chains we define as model-based engineering processes focussing on SysML models as central elements for the definition and description of the system under development. The objective of this article is to analyse the state of the art and practice of the application and implementation of SysML process chains and present a framework for developing a SysML process chain. Therefore, we conduct a systematic literature review (SLR) to identify applications of SysML process chains and derive the different methods and technologies for data transfer and integration within the process chains. Leveraging on findings out of the SLR, we introduce a framework for developing SysML process chains. This approach shall support interdisciplinary engineering activities through better communication and collaboration of different engineering departments. A crucial element to address the named challenges is the realisation of an appropriate data transfer and transformation process in the process chain.

1.1. Model-based Systems Engineering

MBSE can be understood as the application of formalised representations (models) of systems to perform Systems Engineering activities, like system requirements and design definition and verification and validation activities [4,12]. The objective of MBSE is to integrate the results of the Systems Engineering activities into a consistent system model as a central data repository. Associated benefits of MBSE described in the literature are very broad [2,12] and include efficient support of different engineering activities as well as project management due to a better collaboration of different engineering domains [12]. Frequently mentioned benefits of MBSE include [2] *increase of product quality, reuse of system elements, better system design and system architecture, comprehensive assessment of changes and their impact on the system, improved requirements management, earlier system validation and verification*, and *improved traceability*. As these benefits are very generic, there is little empirical evidence for those [2]. However, MBSE addresses several challenges in interdisciplinary engineering. Successful implementation of MBSE requires four essential elements [3]:

1. ***System model***, representing the system under development.
2. ***Modelling method***, defining what has to be modelled, when and how during the engineering process.
3. ***Modelling language***, defining the model elements based on syntax and semantics.
4. ***Modelling tool***, incorporating the modelling rules based on the defined modelling language and containing the underlying data model.

Nevertheless, the implementation of MBSE often faces challenges, like lack of know-how, inconsistent tool chains and missing acceptance of new approaches in the organization [13]. Huldt and Stenius [6] additionally point out that a successful implementation also depends on management support.

1.2. System models as integrating frameworks

System models are a primary artefact of MBSE and serve as an integral part of the technical baseline of the system as they define the requirements, structure, behaviour and parameters of the evolving system of interest [4,12]. Friedenthal [4], therefore, underlines the integrative character of the system model within the development context, as it serves as a consistent source for system specification, design, analysis, and verification information, see Fig. 1. Thus, the system model provides the context and inputs for more detailed domain-specific design as well as verification activities (downstream activities). Moreover, it relates requirements to the system design and provides system design information that is needed for multi-disciplinary analysis and optimisation. Within the downstream process, each technical domain utilises information contained in the system model and complements more detailed specifications, design, analysis, and verification information. This further use and supplementation of the system model or

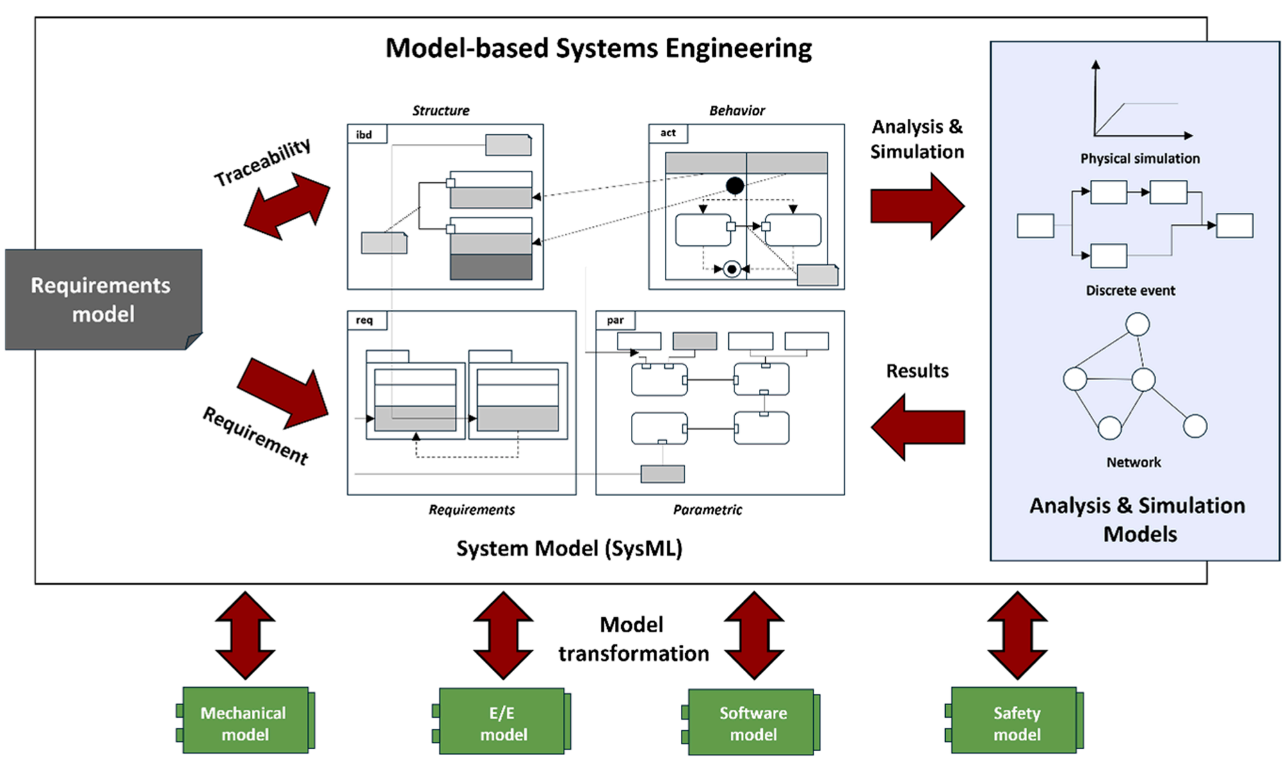

Fig. 1. System Models as integrating frameworks within Model-based Systems Engineering, adapted from [4,12].

single elements of the system model can be considered as a process chain. According to [10] a process chain describes the linkage of different engineering activities to an operational proceeding considering procedural, data interchange and organisational aspects. These process chains involve different steps including data transformation and integration of supplementary information, c.f. section 6. In this article, we focus on the analysis of existing process chains involving SysML models and point out different approaches used to transform data.

1.3. Objective and focus of research

This research investigates the application of process chains in Model-based Systems Engineering. The objective is to understand current applications and implementations of *SysML process chains* in industry and research and to introduce a framework which supports the development of SysML process chains. Based on established literature from the field of Digital Engineering, the term *SysML process chains* is introduced and classified. Performing a systematic literature review current applications of SysML process chains are outlined and a detailed analysis of technologies and methods for implementations is conducted. This analysis provides insights into frequently used methods for model transformation and supplementary information used within SysML process chains. This article is structured as follows: Section 2 introduces the State of the Art regarding process chains in Model-based Engineering and the understanding of SysML process chains. Section 3 outlines the applied proceeding for the SLR. In the Section 4 the results of the performed SLR are presented and subsequently in the Section 5 these results are interpreted. Section 6 introduces a framework for developing SysML process chains and presents an exemplary application. Finally, this publication closes with a conclusion and an outlook regarding further research fields.

2. State of the art

The following section introduces the background of process chains in Model-based Engineering and introduces SysML process chains.

2.1. Application of process chains in Model-based Engineering

The application of process chains within the engineering process is well established for definition and assurance of the detailed system design, analysis of system behaviour and support of production planning. The central element is the utilisation of different process steps which are computer-aided connected [11]. Thus, these process chains are summarised by using the term *CAx process chains*, whereby *x* represents the different engineering use cases, like simulation or process planning. CAx process chains are based on three-dimensional geometric product representation using different geometry models like Constructive Solid Geometry (CSG) or Boundary Representation (B-REP) [14]. Within the CAD-FEA process chain, a volume model is used, discretised into elementary elements (pre-processing) and completed by physical parameters in particular material characteristics as well as external loads and fixtures to perform analysis of stress distribution or deformations. Here the source model is a volume model (B-Rep) representing the shape of the part to be analysed by a number of points, edges and surfaces [15]. In Table 1, the generic properties to define and implement a process chain are described and highlighted using the CAD-FEA process chain. Implementation of CAx process chains promotes the consistent use of product data and reduces the recurring modelling effort and errors. Established process chains are mainly allocated to the mechanical engineering domain, starting with the definition of geometric models. Table 1 presents six properties describing process chains. In Table 1, the generic properties of a process chain are described and examples in the field of CAx and SysML are given.

The introduced properties of process chains in Model-based Engineering provide a generic framework to define and implement process chains. However, there is no specific order to follow. In Fig. 2 the generic procedure within a process chain (control flow) and the necessary data exchange between each process step (object flow) are illustrated.

2.2. SysML process chains

Referring to [10], a process chain describes the linkage of engineering processes to an operational proceeding considering procedural, data interchange and organisational aspects. Each process step can be applied autonomously but is also related to the previous and following process steps. Thereby, process chains can also be understood as the successful deployment and interchange of digital product data and organizational circumstances. Within a process chain, the result of the previous process step serves as an input variable to the following process step. The initial set of product data is mainly based on digital models, like CAD models, which are created to describe the product under development. With proceeding development, the data set will be extended, for instance by simulation or quality data.

Considering MBSE processes, in addition, to the domain-specific models, SysML models are used to describe the structure, behaviour and parameters of the system based on requirements on an abstract level [4]. SysML models are typically developed earlier during the engineering process and serve as inputs for domain-specific models, like CAD models in the downstream process. The increasing use of SysML models as digital representations of the evolving system enables the definition of new or extended process chains. These process chains integrate SysML models as core elements and will be called *SysML process chains*. Thus, a SysML process chain must contain a SysML model to support different engineering tasks within MBSE. An example of a SysML process chain

Table 1
Properties to characterise process chains and examples in the field of CAx and SysML.

Properties	Description	Example CAx process chain	Example SysML process chain
Purpose	Defines the reasons for defining process chains.	Use of CAD geometry data (volume and surface models) to analyse and simulate different designs	Automated test case generation for safety analysis based on behaviour models
Initial / source model	Defines the initial product model, which provides simultaneous the initial product data set.	CAD model; Volume and surface models, mostly as B-Rep models	SysML model; activity diagram
Target model	Defines the target model, which shall be created based on the initial product data set.	Calculation models e.g. systems of equations (FEA model, CFD model, MBS model)	Software model; Intermediate Black box Model
Data transformation	Defines how data out of the initial product data set will be selected and transformed to be processed.	Data selection from CAD model	Graph-based data transformation; XML export of activity diagram and transformation in a directed graph
Supplementary information	Defines required additional data, which is needed to set up the target model.	Physical parameters, like material characteristics.	None
Result interpretation and feedback	Defines how the result will be interpreted and how feedback will be provided to the previous steps in the process chain.	Plausibility checks using visual presentations, feedback or changes using integrated modelling tools.	Test case script according to the test coverage criterion and the test case generation algorithm.

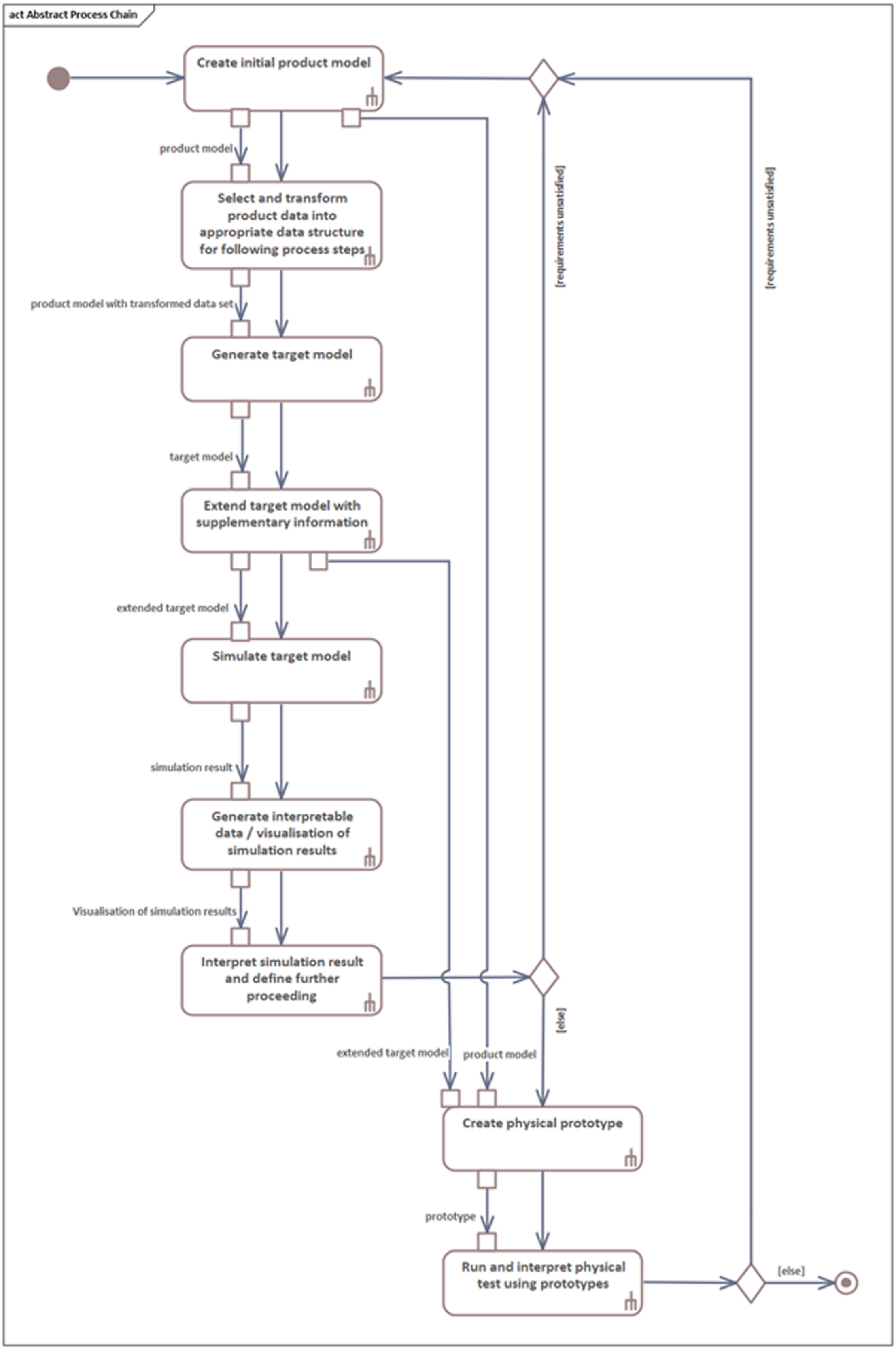

Fig. 2. Proceeding (control flow) and data exchange between process steps (object flow) within an abstract process chain.

containing the automated generation of test cases for safety analyses is shown in Table 1.

The main differences between CAx and SysML process chains are the considered engineering purpose, the applied data type and the data transformation approaches within the process chain. CAx process chains are based on geometric models and their specific representation based on points, edges, surfaces and engineering activities reusing volume models or product structures of the mechanical domain. In contrast, SysML process chains refer to product models realised using system modelling language and include aspects like domain crossing requirements, behaviour, structure, and parameters of the system to be developed. The underlying SysML models use concepts and relations between these represented in different diagrams to describe the system as a whole.

2.3. Distinction between tool chains and process chains

This section introduces the core differences between tool chains and process chains in the context of MBSE. Tool chains are defined as combined modelling, simulation or design tools [16] which can support or construct a system engineering workflow [17]. Based on these tool chain features, three main aspects of MBSE tool chains can be derived:

1. A tool chain shall support executing Systems Engineering activities along the system life cycle by combining the corresponding engineering tools.
2. A tool chain shall enable consistent information transfer and support model transformation approaches.
3. A tool chain connects engineering tools and provides interfaces integrating tools from an existing tool landscape.

In contrast to tool chains, process chains focus on the operational proceeding of engineering tasks considering procedural, data interchange and organisational aspects [10]. Therefore, the main subjects of interest within a process chain are the engineering artefacts as the results of each process step. The objective of tool chains is the linkage of engineering tools, which is important to enable the efficient development of the individual engineering artefact. A core aspect of both types of chains is the assurance of a suitable information flow between engineering processes to enable efficient engineering. To conclude, process chains focus on the operational execution of engineering tasks, therefore, the handover of the result of each process step to the subsequent process is crucial. Tool chains are a valuable approach for realising these handover processes because their main objective is the combination of engineering tools to ensure data and information exchange. An essential element to enable consistent data and information transfer is the consideration of model transformation approaches, these will be a central element of the following SLR.

3. Research methodology

This paper investigates the application and implementation of SysML process chains in literature. This section introduces the used procedure for a SLR, based on [18]. Systematic literature reviews focus on a comprehensive evaluation and interpretation of all available research relevant to a particular topic and thereby depict a trustable and verifiable methodology for literature studies [18]. This review is structured into five steps:

1. Research objective and questions
2. Search process
3. Inclusion and exclusion criteria
4. Quality assessment
5. Data extraction and analysis

The single steps are reported in the following sections.

3.1. Research objective and questions

The increasing acceptance and application of SysML models in MBSE [3] enable an earlier creation of the required product data sets to define process chains in addition to existing domain-specific models. This article will analyse the application of SysML process chains based on the introduced properties of process chains, see Table 1. Therefore, the overall research goal is formulated in Table 2 following the Goal-Question-Metric approach [19].

Based on the defined research goal, a main research question was derived:

Main RQ: Which engineering use cases apply SysML process chains and how are these implemented?

To answer this main research question, in Table 3 more detailed research questions were defined based on the process chain properties introduced in Table 1.

To analyse these research questions, the following section describes the search process of the performed literature study.

3.2. Search process

The following search string was applied as a keyword search to identify the related publications:

"process-chain" OR "process chain" OR "tool-chain" OR "tool chain"

AND "SysML" AND "MBSE"

NOT "Supply Chain"

By considering Google Scholar as a representative database, 412 publications were identified (Status November 2023).

3.3. Inclusion and exclusion criteria

The inclusion and exclusion criteria outlined in Table 4 are applied to select publications for further analysis. Each paper was evaluated based on the inclusion and exclusion criteria by analysing the paper title and abstract. After applying inclusion and exclusion criteria, the amount of considered publications decreased to 94. Afterwards, these publications were investigated regarding the inclusion and exclusion criteria based on a full-text analysis. Finally, 40 publications are deemed relevant for the detailed literature study.

3.4. Quality assessment

To ensure that all relevant publications are part of the literature review, an automated citation-based search (*snowballing*) was accomplished to retrieve further results, as suggested by [20]. By applying the tool *ResearchRabbit,* 54 additional papers were identified. These papers were again analysed based on the defined inclusion and exclusion criteria which resulted in 9 additional publications. The following full-text analysis excluded 6 publications. Thus, the application of the snowballing process resulted in 3 additional publications to be considered. Overall, 43 publications define the data set for the following literature review. The literature review was conducted by two independent reviewers to verify the defined study criteria and to avoid possible failures during the reviewing process.

The PRISMA (Preferred Reporting Items for Systematic Reviews and

Table 2
Overall research goal.

Purpose	Perform a systematic literature study on the
Issue	application and implementation of SysML process chains in Model-based Systems Engineering by
Object	identifying the basic properties and methods and technologies used for the implementation
Viewpoint	from a research point of view.

Table 3
Derived research questions.

Process chain property	Research question	Numbering
Purpose	What are the motivations of SysML process chains reported in the literature?	RQ 01
Purpose	What is the engineering purpose of the defined SysML process chain?	RQ 02
Initial / source model	What serves as the initial source model?	RQ 03
Target model	What is the target model of the SysML process chain?	RQ 04
Data transformation	What are the applied data types within the SysML process chain?	RQ 05
Data transformation	Which model transformation techniques are applied to transfer information from the source model to the target model?	RQ 06
Supplementary information	What supplementary information is required to build up the target model?	RQ 07

Table 4
Inclusion criteria (IC) and exclusion criteria (EC).

Type	ID	Criteria
IC	1	We include papers describing tool chains.
	2	We include papers, which describe process chains where the SysML model is the target model.
	3	We include only peer-reviewed papers out of journals or conference proceedings.
	4	We include only papers, which are published after the release of the SysML, meaning April 2006.
EC	1	We exclude papers, which do not contain process chains to support Systems Engineering processes.
	2	We exclude papers only describing a vision.
	3	We exclude papers focussing on production or manufacturing process chains and supplier management.
	4	We exclude papers only describing MBSE or SysML benefits.
	5	We exclude papers available only in kind of abstract.
	6	We exclude papers not written in English.
	7	We exclude duplicates.

Meta-Analyses) flowchart [21], summarizes the result of the search process, starting with the initial number of identified publications, screening the publications based on inclusion and exclusion criteria and finally the number of publications to be included in the literature study. Fig. 3 presents a slightly changed and extended version of the PRIMSA flowchart, which also includes the identified publications based on citation-based analysis (*snowballing*).

3.5. Data extraction and analysis

The 43 included papers were investigated to extract and collect data to obtain the answers to the defined research questions. Therefore, in the first step, the ten publications with the highest number of citations were analysed to define initial categories for clustering (*initial literature review*). Based on this, the remaining 33 publications were reviewed and clustered based on the defined categories (*exploratory literature review*). Thereby, the defined categories have been partially replaced or extended. Fig. 4 shows how the number of publications is distributed over the publication years. It can be observed that there has been a constant growth in the number of publications on this topic in recent years and that the number has reached a particularly high level in the last years. The study results are presented in the following section.

4. Study results

This section summarises the results of the literature review. The results are structured according to the research question introduced before. Out of the 43 investigated publications, 24 present an application of a SysML process chain, while 6 publications describe an idea or vision about a SysML process chain. The remaining 13 publications present just elements of a process chain and were consequently not considered in this differentiation.

4.1. *Motivation and purpose of SysML process chains*

Based on the generic purpose of fostering information consistency and reuse of different engineering tasks, SysML process chains are implemented for different purposes. Following the first two research questions, this section introduces the motivation and purposes of SysML process chains found in the review.

RQ 01 focuses on the overall motivation of the described SysML process chain. The aim is to determine what the SysML process chains are generally used for. On this more abstract level, we distinguished between *technical* and *technical management* tasks based on [22]. Furthermore, we defined the criterion *linking domain-specific engineering* which is focussing on the collaboration between different engineering disciplines. Thus, the bigger part of SysML process chains (22 out of 27 publications) is applied to *support technical engineering tasks,* like safety analysis [23] or test case derivation [24]. Furthermore, SysML process chains are used to improve collaboration between different engineering domains and to support technical management processes, such as variability management [25].

SysML process chains pursue different goals. To address the second research question (**RQ 02**), we analysed which purposes are reported for the implemented process chains. Table 5 summarises the defined categories. These categories highlight different engineering tasks to be performed in SE and the purpose of the process chain. An explanation for each category is given in Table 5.

The main purpose of SysML process chains is *system behaviour simulation (8 out of 24 publications)* and the *automated execution of verification and validation (6 out of 24 publications)* activities. Also, the use of SysML models as input for *safety analysis* is frequently stated in the literature. Fig. 5 illustrates the combined study results of RQ 01 and RQ 02.

The combination of the first two RQs indicates which motivation results in which purpose of a process chain. As visible in *Fig. 5*, the main motivation *Support technical engineering task* results in three different purposes: *Model-based safety analysis, Automatical execution of verification & validation* and *System behaviour simulation.* The purpose *Model-based safety analysis*, for example, is to carry out security analyses at an early stage using the developed system architecture to ensure security compliance at an early stage [26]. Further purposes assist in the early assessment of system behaviour in accordance with specified requirements [27]. Further engineering purposes of SysML process chains are to ensure *Continuous Systems Engineering, and* traceability and possess original motivation in linking domain-specific engineering and supporting engineering tasks or management processes [28]. Moreover, different SysML process chains were identified that support specific engineering tasks, like the *definition of system interfaces*, the *automated creation of domain models,* or to *generate a basic system architecture.*

4.2. *Structure of SysML process chains and applied model transformation types*

After identifying the motivation and purpose of SysML process chains, this section describes the structure of the identified process chains based on the introduced process chain properties (Table 1). Especially, the applied data and model transformation types are analysed.

Focusing on RQ 03, the connection from purpose to source model, providing the initial data set for the process chain, is investigated. Fig. 6 shows that SysML models are mainly used as source models. Thereby, models describing the *structure* and *behaviour* of the system are the most widely used.

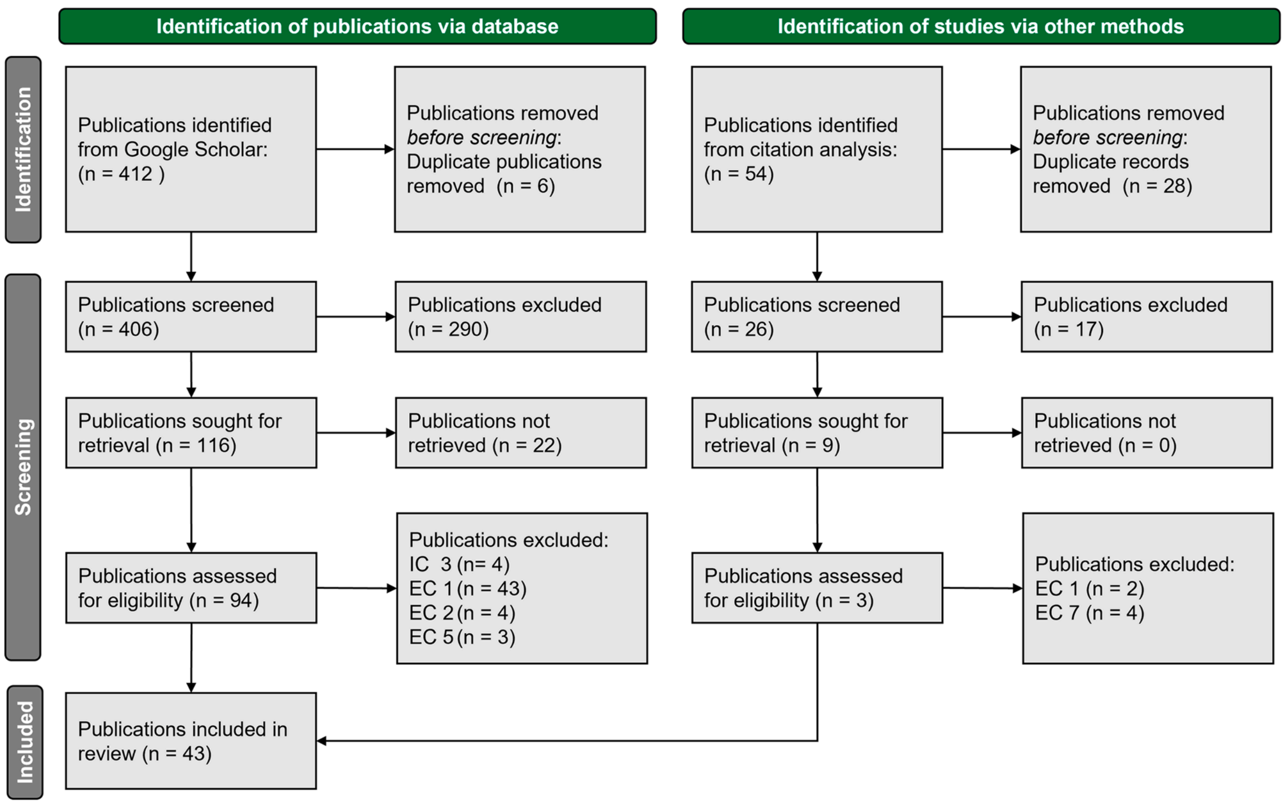

Fig. 3. PRISMA flow chart.

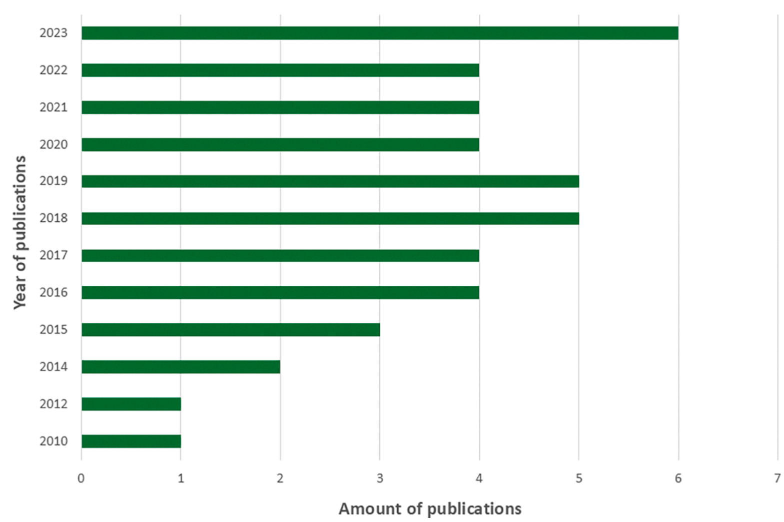

Fig. 4. Publication year of the investigated publications.

Only in some cases, other model types, like *CAD models*, are utilized to initiate a SysML process chain. Here the SysML model is part of the process chain but does not serve as a source model.

By investigating **RQ 04** the target model of the SysML process chain was identified. As represented in Fig. 7, the target models that are used most often are *simulation models*. These are created to enable a simulation of the system behaviour, for instance. Linked to the source models reveals that the simulation models originate from different SysML models. Most of these models are structure and behaviour diagrams followed by requirement and parameter models. Further identified target models are *system models, models for safety analysis* or specific domain-specific models which also use different SysML models as sources. The *system model* in this case represents an abstract description of the considered system to realize interdisciplinary engineering tasks, like the management of variability or to represent the interfaces between different engineering domains [29]. Identified examples of domain-specific models are *software models*, which were used for automated source code generation, or *CAD models* to enable a succeeding CAx process chain [27].

RQ 05 refers to the applied data type within the process chain. The study result shows that within SysML process chains, most often tool-independent data types are used to transfer data from one process step to another. The *XML-file* was most frequently stated in the publications. Other data formats used are strongly application-specific, like the use of

Table 5
Identified purposes of SysML process chains.

Category	Explanation
Model-based safety analysis	This category includes all publications which use the initial source model as input or basis for safety analysis, such as the generation of concrete safety artefacts or the assurance of model consistency.
System behaviour simulation	Within this category, all publications are listed that utilise the initial model for system behaviour description to enable behaviour simulations, like physical simulations.
Continuous Systems Engineering	This category includes all publications which focus on coherent and consistent Systems Engineering. No further explanation about the detailed purpose is included.
Generate basic architecture	This category contains all publications which describe a SysML process chain where a domain-specific architecture will be generated based on the system architecture.
Automated execution of verification and validation	The category *automated execution of verification and validation* includes all SysML process chains which enable automated verification and validation activities to ensure the developed system structure and behaviour.
Automated creation of domain models	This category summarizes all SysML process chains which create domain models out of the initial system model.
Define system interfaces	In this category, all publications are included which use an initial source model to derive concrete system interfaces.

ue4-files to enable visual simulations by use of Unreal Engine 4 [30].

The different types of model transformation within the process chain were investigated referring to **RQ 06**. In general model transformation describes the unidirectional transformation of models or model elements into other models, such as the transformation of domain-specific models to simulation models [31]. Table 6 summarises and explains the identified model transformation types that are used to implement the SysML process chains.

Mainly, the development of specific *application programming interfaces (API)* is established to transform the data from the initial source model to the target model. Other transformation approaches are based on *knowledge graphs* [32] or *meta-models* [33]. Graph-based approaches apply languages, like Triple Graph Grammars (TGG), which are used as intermediaries to enable a semantical appropriate data transformation. Meta-models offer a similar approach for semantical data mapping and transformation. Thereby, the semantical linkage is often enabled by the use of model elements on higher abstraction levels. In three analysed publications, the model transformation was performed by specific software tools, these were allocated to the category *middleware*. The category *file-based data exchange* represents all process chains where the required data can be exchanged by use of standardized import and export functions.

Fig. 8 combines the identified data types within the process chain with the applied model transformation approach. Thereby, the primary use of XML-files in different transformation types, like Application Programming Interfaces, becomes obvious.

Focussing on **RQ 07**, the necessary supplementary information to

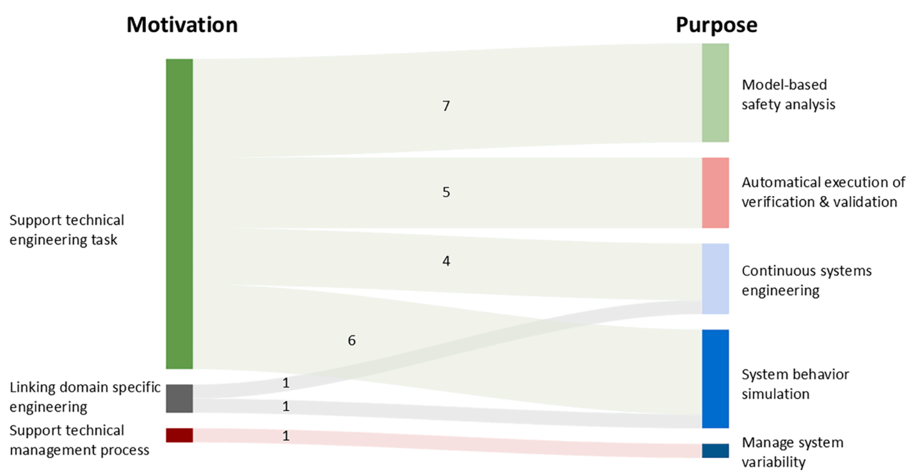

Fig. 5. Motivation and purpose of SysML process chains.

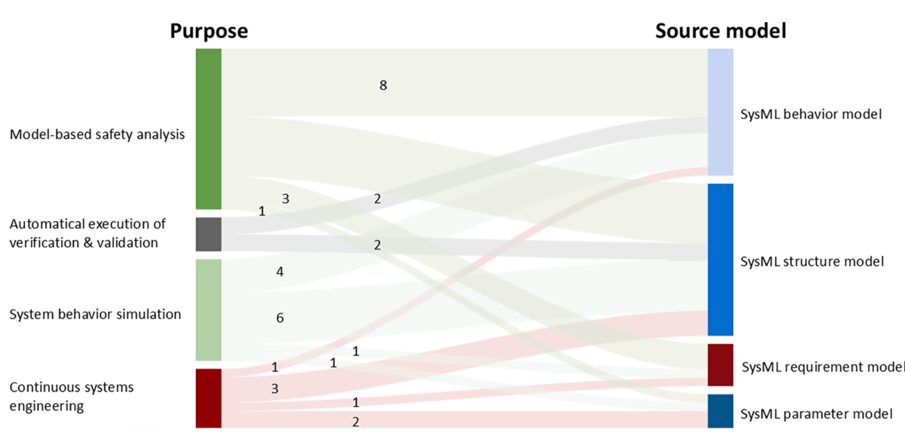

Fig. 6. Linking of purpose and source model of the SysML process chain.

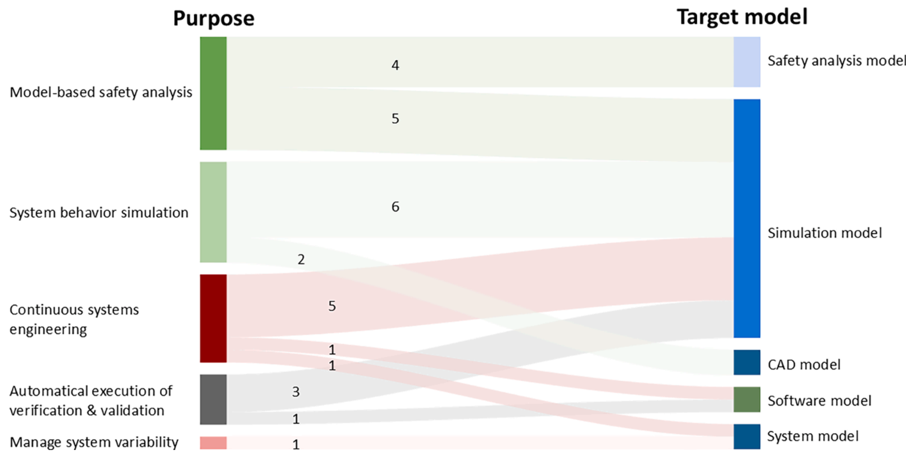

Fig. 7. Linkage of purpose to target model of the SysML process chain.

Table 6
Explanation of identified model transformation types.

Model transformation type	Explanation
Application Programming Interface (API)	An *Application Programming Interface* is an application-specific tool which enables a tool to read and interpret data that is normally not in scope. These interfaces are mainly realised on the source code level and enable communication between different authoring tools.
Semantical data mapping and meta-models	*Semantic data mapping* is an approach for establishing connections between different models or data by using, for instance, semantic web technologies. It involves mapping the data elements from one model to another. For representation of the data mapping meta-models are often utilised.
Graph-based data transformation	The application of *graph-based approaches* enables the transformation of specific models to unified model representations. These representations can be used for more detailed analysis or transformed into the target model.
Model transformation	The general category *model transformation* summarizes publications which show a model transformation during the SysML process chain without any further explanation about the applied transformation type.
Middleware	*Middleware* refers to application-neutral programs that connect applications in a way that their complexity and infrastructure are concealed. During the study, this category was selected when an application was detected which was used as middleware without any further explanation about the model transformation process.
File-based data exchange	The category *file-based data exchange* was selected when the data exchange was realised by data files without any kind of data transformation.

create the target model was determined. In most cases, no supplementary information is required in addition to the applied data type (RQ 05) to create the target model. Within the considered literature only *configuration models* (1 reference), *physical values* (3 references) and *geometric dimensions* (1 reference) are stated as supplementary information. Consequently, this information is required to create the target model, for instance, in the right configuration.

The following section will discuss the study results to answer the defined research questions.

5. Findings

This literature review investigates the usage and implementation of SysML process chains. To answer the introduced main research question, eight research questions were derived based on the identified properties, see section 3. In the following section, the key findings drawn from the review will be presented.

5.1. *Application and purpose of* SysML *process chains*

The application of SysML process chains in the literature mainly focuses on technical engineering tasks, like the definition of the system architecture. Partly SysML process chains are used to support technical management processes, like variability management or to improve the collaboration of different engineering departments. As the main purpose of SysML process chains, the early assurance of the defined system architecture was identified. Therefore, behaviour simulations as well as verification and validation activities were performed in parallel with the system architecture development. This results in a more target-oriented and efficient engineering process. A further purpose of SysML process chains is the execution of safety analysis during the architecture development. This enables early adjustments in the system architecture regarding safety requirements. Furthermore, SysML process chains can increase the system understanding based on early system behaviour modelling and simulation.

5.2. *Structure of* SysML *process chains*

The structure of SysML process chains strongly depends on the specific application case. However, in general, it can be stated that a SysML process chain is initiated by a SysML model to support following downstream engineering tasks. The initial SysML model was distinguished into structure, behaviour, requirement and parameter models. In Fig. 9 the source (left side) and target models (right side) are represented. Thus, it becomes obvious that mainly structure and behaviour models were applied as source models. This is noticeable because established engineering approaches, like RFLP [34] emphasise the definition of requirements as the initial point for the engineering process. The target models of the SysML process chains are mainly various kinds of simulation or safety models to enable an early simulation of the system behaviour. In addition, there are domain-specific target models, like software or CAD models. Here, the initial SysML model can support creating domain models, improve collaboration between different engineering departments and maintain the consistency between the source and target model.

An essential aspect of a process chain is the realisation of the data transformation process. In the case of SysML process chains, mainly application-specific interfaces (API) were developed to enable appropriate data exchange. Consequently, the need for standardised data interfaces can be identified. Further data transformation types that are frequently used were the linking of data on a more abstract level by applying meta-models or the use of graph-based data transformation

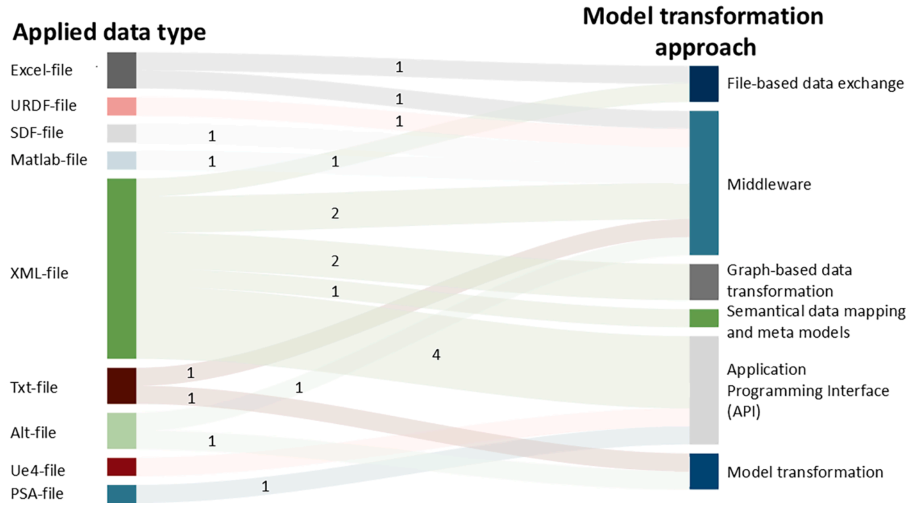

Fig. 8. Applied data types in connection with model transformation approach in the SysML process chain.

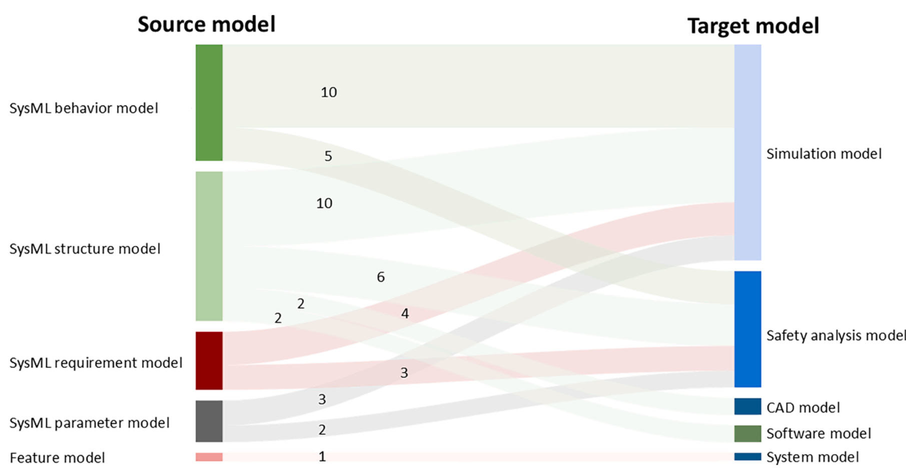

Fig. 9. Determined linkages between source and target models based on analysed SysML process chains.

approaches. The data exchange itself is primarily performed by the use of data files, thereby the neutral data format XML is dominating. In comparison to established process chains, SysML process chains do not require further supplementary information to set up the target model. In some cases, configuration information is required, but overall, it can be determined that all required pieces of information are already included in the source model and can be transferred into the target model.

5.3. Summary and discussion

The objective of this publication was to answer the introduced main research question considering the application and implementation of SysML process chains. This section summarises the key findings of the conducted literature study.

The main application of SysML process chains is the linkage of the architecture definition process with the system verification process to enable a parallelised development and verification of the system architecture. Thereby, especially the use of simulation approaches to verify the current system architectures is dominating. A SysML process chain is typically initiated by a SysML model as a source model and with the use of data transformation types, such as APIs or semantic links, the required data set is provided to create application-specific simulation models as target models. The performed literature investigation shows also that SysML models, based on their formal and abstract character, are appropriate to be used as source models for SysML process chains. The created data set is important for and can be reused by various engineering tasks. Furthermore, the use of XML-files as a neutral data exchange format enables a linkage of different authoring tools within the process chain.

During the performed literature study, different findings regarding a possible enhancement of SysML process chains were identified. These findings will be explained in the following paragraph. An advisable enhancement of the current SysML process chains is the greater involvement of requirements models. These models can be part of the SysML model but can also be other kinds of requirements models. This extension can support the engineering process to ensure that the developed system satisfies the customer's requirements. Furthermore, a more intensive integration of parameter models could increase the quality and validity of the simulation models, which are based on the presented study results, the main outcome of the SysML process chain. Finally, we identified that predominantly the simulation results did not automatically exchange back to the source model. This enhancement of SysML process chains could enable a higher automated design optimisation process.

Within the following section, the development of SysML process chains will be explained and an application example will be presented.

6. Development and application of SysML process chains

This section introduces a framework for developing SysML process chains and presents an exemplary realised process chain connecting SysML and CAD models.

6.1. Initial framework for developing SysML process chains

Leveraging on the previously introduced properties (Table 1), an initial framework for developing SysML process chains will be introduced. A central element of a SysML process chain is the existence of a SysML model as a source or target model. Fig. 10 presents the framework including the required steps to develop a SysML process chain.

The first element for developing a process chain is the definition of the process chain's purpose. This is crucial for defining the required target model and identifying the initial source model. The performed literature study presents that SysML process chains are mainly applied in the early stages of Systems Engineering. Therefore, the source model is primarily a SysML model which describes the structure, behaviour, requirements or parameters of the system of interest. The characteristics of the target models are more heterogeneous based on the considered use case. In literature, these are mainly used to analyse or simulate the source model in order to get early feedback about the system's behaviour. A further element of a process chain is the application of an appropriate data transformation approach. This approach must select the required data from the source model and transform this data into the needed conditions of the target model. For processing the created target model, partial supplementary information is necessary, like real physical data for simulation. Finally, the generated results must be interpreted and transferred to the previous process steps. This can lead to a changed source model, data transformation approach or supplementary information.

The following section introduces a developed process chain connecting SysML and CAD models to enable a more efficient architecture definition process.

6.2. Realised process chain for connecting SysML and CAD models

Interdisciplinary engineering processes, like architecture definition, require both SysML models to describe the overall functions and structure as well as CAD models to define the detailed design of the system. To improve collaboration and communication between the different engineering departments and to avoid model inconsistencies a SysML process chain to connect SysML and CAD models shall be developed. Therefore, the introduced framework was applied. Fig. 11 presents an implementation concept for realising this SysML process chain.

The overall purpose of the SysML process chain is to support interdisciplinary engineering activities. Hereby, we focus on the architecture definition process. In more detail, the process chain shall connect Systems Engineering and mechanical engineering processes to improve collaboration between the different engineering departments and maintain consistency between SysML and CAD models. Based on this purpose, we defined the SysML model as the source model because the definition of the system requirements, function, and overall structure is typically earlier in the engineering process as the development of the detailed system design. Thus, the CAD model is defined as the target model within the SysML process chain. A file-based data exchange between SysML and CAD tools realises the data transformation. We use XML (Extensible Markup Language) files with XMI (XML Metadata Interchange) data structure as data type. Usually, SysML tools can import and export this data type without further effort. This enables selecting and extracting the needed data from the SysML model. However, CAD tools are typically not able to import XML data with XMI data structure. Therefore, we decided to develop a Python-based API that extends the functionalities of the CAD tool to enable the import and export of XMI files. Combining a file-based data exchange with the API shall fulfil the data transformation during the SysML process chain. Design decisions made during the development of the SysML model can now be better considered during the CAD modelling (target model). Furthermore, consistency between the source and target model will be ensured through an automated read-in function of components, functions and requirements into the CAD model. The result of the process chain is the detailed design of the considered system in case of a CAD model. Based on the introduced framework, the final step is to provide feedback and results to the previous processes of the process chain. In our realisation, the detailed design (target model) shall also be exported to the initial source model (source model) in order to avoid inconsistencies. Therefore, the developed API extends the CAD tool by an export function which creates XML files with a data structure that is readable by the SysML tool. In summary, we developed a SysML process chain that connects SysML and CAD models regarding better interdisciplinary collaboration and bidirectional data flow. Table 7 summarises the properties of the realised SysML process chain.

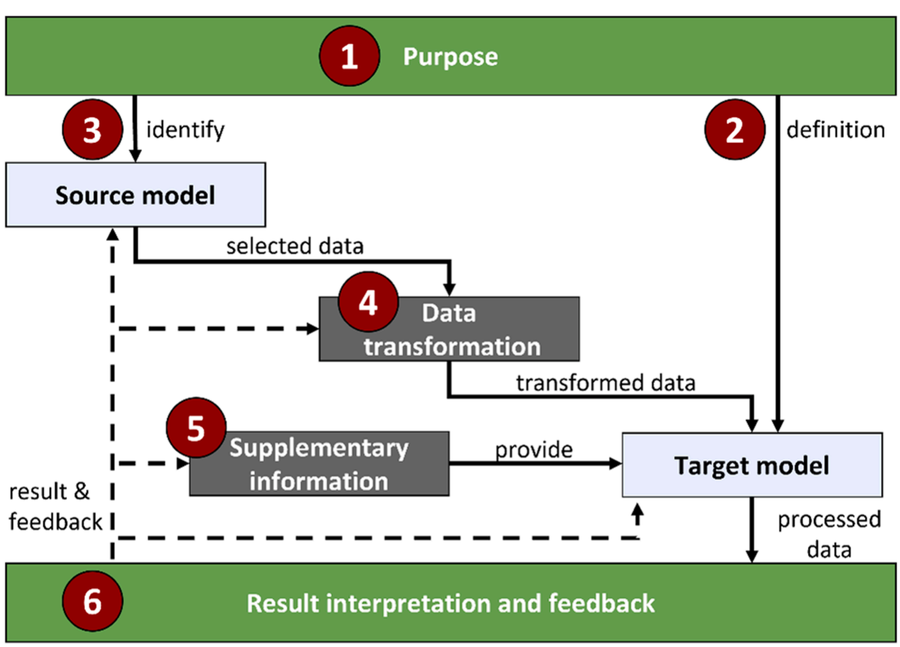

Fig. 10. Framework for developing SysML process chains.

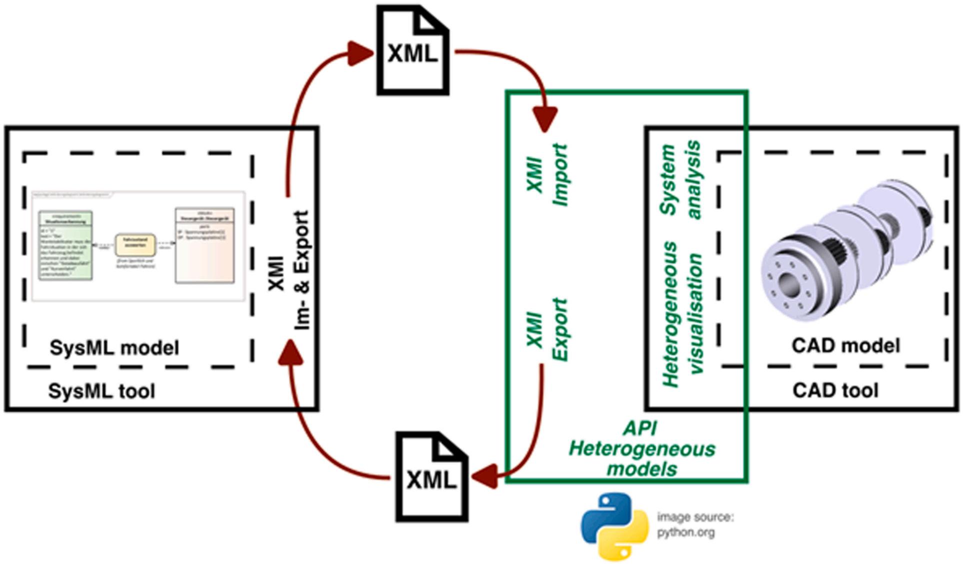

Fig. 11. Implementation concept for SysML - CAD process chain based on [35].

The developed API provides further functionalities to the CAD tool to support architecture definition and analysis processes. This is especially the integration of SysML and CAD model elements into an integrated model visualisation. More detailed information can be found in [35].

Fig. 12 presents the developed SysML process chain based on the introduced properties. Thereby, the logical order for applying the process chain and the required data exchange processes between the individual process steps are defined. Moreover, further required input factors for each process step are included in the visualised process chain.

7. Conclusion and future research

In this publication, a systematic literature review was conducted to investigate applications and implementations of SysML process chains. Therefore, based on the established approach of CAx process chains, the concept of SysML process chains was introduced. SysML process chains represent linked tasks to support Systems Engineering activities relying on SysML models and the corresponding product data (concepts and relations). To enable appropriate textual screening, the properties of process chains were analysed and used to derive eight study questions for the literature review. Finally, 43 publications were analysed. Based on this analysis, it can be concluded that existing SysML process chains are predominantly used to support *architecture definition* as well as *verification and validation* activities within Systems Engineering. Thereby, the SysML process chains aim at the linkage of these activities to enable a joined development and an early verification of the developed system architecture. The structure of the SysML process chain depends on the specific use case. Overall, it can be stated that SysML models are mainly used as source models for the SysML process chain to provide the data set for application-specific simulation models as target models. To enable consistent data transfer, model transformation approaches are an essential part of SysML process chains. Thereby, especially application-specific interfaces (APIs) and semantic interconnections based on meta-models are applied. Leveraging on the described properties of process chains and the findings of the literature review, we introduce an initial framework for developing SysML process chains and present an exemplary application of the proposed framework. This implementation presents a SysML process chain connecting SysML and CAD models in order to improve communication and collaboration in interdisciplinary engineering disciplines and maintain consistency between these different model types. The emphasis here lies in realising a consistent data transfer and transformation process between elements of SysML models, like blocks, and CAD models, like single parts. Finally, the paper discusses enhancements of SysML process chains, for instance, by more extensive integration of requirements models into the SysML process chain. With the introduction of SysML process chains, a consistent linkage of SysML models, as an elemental part of the MBSE approach, and domain-specific models can be achieved. This linkage must consider procedural, organisational as well as data exchange and transformation aspects. Future research mainly focuses on the enhancement of the initial framework. Especially, the relations between the different process steps will be further investigated, like a recommendation of the data transformation type based on the process chain purpose. Further research will focus on the following aspects of SysML process chains:

- Implementation of SysML process chains to integrate interdisciplinary and domain-specific architecture design in Systems Engineering.
- Investigation of AI-based methods for model and data transformation within SysML process chains, e.g., based on ontology learning to enable more robust and adaptive transformation of different source model qualities.
- Investigation of the benefits of combined visualisation of domain-specific and cross-domain information for knowledge reuse by heterogenous product models.

Table 7
Properties of realised SysML process chain.

Properties	Process chain for connecting SysML and CAD models
Purpose	Connected Systems Engineering and mechanical engineering processes to improve interdisciplinary collaboration and model consistency for conducting a comprehensive system architecture development.
Initial / source model	SysML model
Target model	CAD model
Data transformation	Python-based API with export and import functions using XML files with XMI data structure.
Supplementary information	None
Result interpretation and feedback	Detailed system design leveraging on a linked system architecture. Design decisions within CAD modelling will be returned to the SysML model to ensure model consistency.

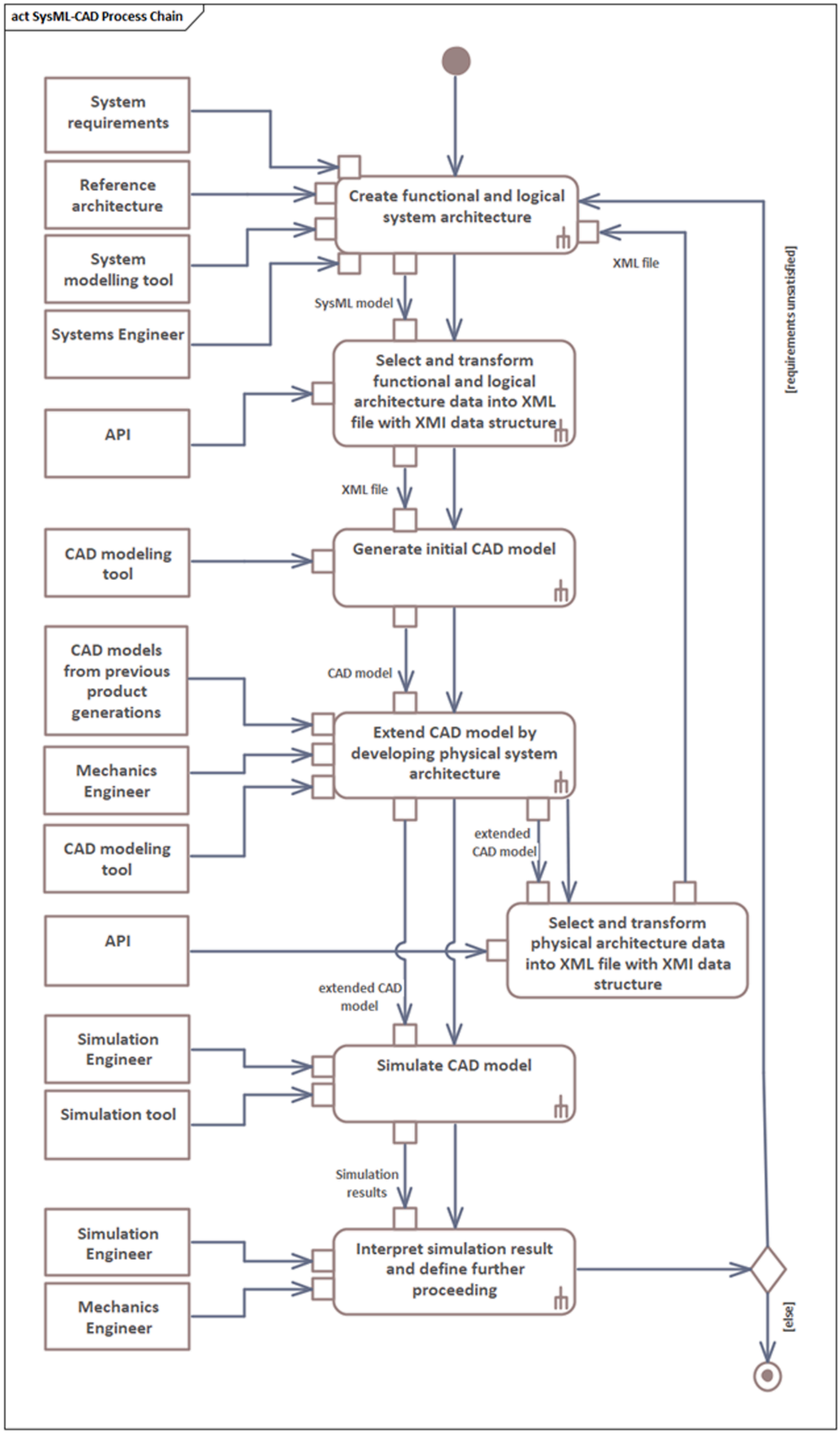

Fig. 12. Visualisation of SysML-CAD process chain.

These research works will contribute to more effective modelling and reuse of models within the different Systems Engineering activities.

CRediT authorship contribution statement

Thomas Schumacher: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Chris-Kilian Müller:** Writing – original draft, Visualization, Methodology, Investigation. **David Inkermann:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

David Inkermann reports financial support was provided by Lower Saxony Ministry of Science and Culture (grant number ZN3493). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Partially funded by the Lower Saxony Ministry of Science and Culture under grant number ZN3493 within the Lower Saxony “Vorab“ of the Volkswagen Foundation and supported by the Center for Digital Innovations (ZDIN).

Data availability

Data will be made available on request.

References

[1] D. Inkermann, Shaping method ecosystems - structured implementation of systems engineering in industrial practice, Proc. Des. Soc. 1 (2021) 2641–2650, https://doi.org/10.1017/pds.2021.525. Aug.
[2] K. Henderson, A. Salado, Value and benefits of model–based systems engineering (MBSE): evidence from the literature, Syst. Eng. 24 (1) (2021) 51–66, https://doi.org/10.1002/sys.21566.
[3] M.C. Berschik, T. Schumacher, F.N. Laukotka, D. Krause, D. Inkermann, Mbse within the engineering design community – AN exploratory study, Proc. Design Soc. 3 (2023) 2595–2604, https://doi.org/10.1017/pds.2023.260.
[4] S. Friedenthal, A Practical Guide to SysML: The systems Modeling Language, 3rd edition, Morgan Kaufman, Waltham, MA, 2014 [Online]. Available: http://proquest.tech.safaribooksonline.de/9780128002025.
[5] E.R. Carroll and R.J. Malins, ‘Systematic literature review: how is model-based systems Engineering justified?’, 2016, [Online]. Available: https://www.osti.gov/servlets/purl/1561164.
[6] T. Huldt, I. Stenius, State-of-practice survey of model-based systems engineering, Syst. Eng. 22 (2) (2019) 134–145, https://doi.org/10.1002/sys.21466.
[7] T.V. Huynh and J.S. Osmundson, ‘A systems engineering methodology for analyzing systems of systems using the systems modeling language (SysML)’, 2006, [Online]. Available: https://hdl.handle.net/10945/40375.
[8] S.C. Spangelo, et al., Applying model based systems engineering (MBSE) to a standard CubeSat, in: 2012 IEEE Aerospace Conference, Big Sky, MT, IEEE, 2012, pp. 1–20, https://doi.org/10.1109/AERO.2012.6187339. Mar.
[9] T. Schumacher, D. Kaczmarek, D. Inkermann, A. Lohrengel, Fostering model consistency in interdisciplinary engineering by linking SysML and CAD-models, in: 2022 IEEE International Symposium on Systems Engineering (ISSE), Vienna, Austria, IEEE, 2022, pp. 1–7, https://doi.org/10.1109/ISSE54508.2022.10005327. Oct.
[10] R. Anderl, P. Castro, CAD/CAM - Auf dem Weg zu Einer Branchenübergreifenden Integration, Springer Berlin Heidelberg, Heidelberg, 1990.
[11] R. Anderl, ‘Virtuelle Produktentstehung’, in Dubbel, K.-H. Grote, B. Bender, and D. Göhlich, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2018, pp. 2012–2028. doi: 10.1007/978-3-662-54805-9_157.
[12] International Council on Systems Engineering, Systems Engineering handbook: a Guide For System Life Cycle Processes and Activities, 4th Edition, Wiley, Hoboken, N.J, 2015.
[13] J. Gausemeier, R. Dumitrescu, D. Steffen, A. Czaja, O. Wiederkehr, C. Tschirner, *Systems Engineering in Industrial Practise*. Paderborn: Heinz Nixdorf Institut, Universität Paderborn, Lehrstuhl für Produktentstehung, Fraunhofer-Institut für Produktionstechnologie IPT – Projektgruppe Entwurfstechnik Mechatronik, UNITY AG, 2015.
[14] VDI, *3D product modelling - technical and organizational requirements - procedures, tools, and applications - cost-effective practical use*, VDI 2209.2009.
[15] C.M. Hoffmann, Geometric and solid modeling: an introduction, 2nd. print. Morgan Kaufmann series in Computer Graphics and Geometric Modeling, Morgan Kaufmann, San Mateo, Calif, 1993.
[16] J. Ma, G. Wang, J. Lu, H. Vangheluwe, D. Kiritsis, Y. Yan, Systematic literature review of MBSE tool-chains, Appl. Sci. 12 (7) (2022) 3431, https://doi.org/10.3390/app12073431.
[17] J. Lu, D. Chen, D. Gürdür, M. Törngren, An investigation of functionalities of future tool-chain for aerospace industry, INCOSE Int. Symp. 27 (1) (2017) 1408–1422, https://doi.org/10.1002/j.2334-5837.2017.00437.x. Jul.
[18] B. Kitchenham, Procedures For Performing Systematic Reviews, Department of Computer Science, Keele University, 2004.
[19] V.R. Basili, G. Caldiera, D. Rombach, The Goal Question Metric Approach, Department of Computer Science, University Of Maryland, 1994.
[20] B. Kitchenham, P. Brereton, A systematic review of systematic review process research in software engineering, Inf. Softw. Technol. 55 (12) (2013) 2049–2075, https://doi.org/10.1016/j.infsof.2013.07.010. Dec.
[21] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, The PRISMA Group, Preferred reporting items for systematic reviews and meta-analyses: the PRISMA Statement, PLoS Med 6 (7) (2009) e1000097, https://doi.org/10.1371/journal.pmed.1000097. Jul.
[22] ISO/IEC/IEEE, Systems and Software Engineering - System life Cycle Processes, Beuth Verlag, Düsseldorf, 2015, 2015–05.
[23] E. Brusa, Digital Twin: toward the integration between system design and RAMS assessment through the model-based systems engineering, IEEE Syst. J. 15 (3) (2021) 3549–3560, https://doi.org/10.1109/JSYST.2020.3010379. Sep.
[24] Y. Yin, An automated test case generation approach based on activity diagrams of SysML, IJPE (2017), https://doi.org/10.23940/ijpe.17.06.p13.922936.
[25] D. Bilic, E. Brosse, A. Sadovykh, D. Truscan, H. Bruneliere, U. Ryssel, An integrated model-based tool chain for managing variability in complex system design, in: 2019 ACM/IEEE 22nd International Conference on Model Driven Engineering Languages and Systems Companion (MODELS-C), Munich, Germany, IEEE, 2019, pp. 288–293, https://doi.org/10.1109/MODELS-C.2019.00045. Sep.
[26] R.W. Hollmann, A. Schäfer, O. Bertram, M. Rädel, Virtual testing of multifunctional moveable actuation systems, CEAS Aeronaut J 13 (4) (2022) 979–988, https://doi.org/10.1007/s13272-022-00602-5. Oct.
[27] M. Dalibor, N. Jansen, B. Rumpe, L. Wachtmeister, A. Wortmann, Model-driven systems engineering for virtual product design, in: 2019 ACM/IEEE 22nd International Conference on Model Driven Engineering Languages and Systems Companion (MODELS-C), Munich, Germany, IEEE, 2019, pp. 431–436, https://doi.org/10.1109/MODELS-C.2019.00069. Sep.
[28] E.J. Vidal, E.R. Villota, SysML as a tool for requirements traceability in mechatronic design, in: Proceedings of the 2018 4th International Conference on Mechatronics and Robotics Engineering, Valenciennes France, ACM, 2018, pp. 146–152, https://doi.org/10.1145/3191477.3191494. Feb.
[29] H. Sporer, G. Macher, C. Kreiner, E. Brenner, Resilient interface design for safety-critical Embedded automotive software. Computer Science & Information Technology (CS & IT), Academy & Industry Research Collaboration Center (AIRCC), 2016, pp. 183–199, https://doi.org/10.5121/csit.2016.60117. Jan.
[30] H. Yang, et al., Research on visual simulation for complex weapon equipment interoperability based on MBSE, Multimed. Tools Appl. 83 (5) (2023) 13463–13482, https://doi.org/10.1007/s11042-023-15950-5. Jul.
[31] F. Wilking, D. Horber, S. Goetz, S. Wartzack, Utilization of system models in model-based systems engineering: definition, classes and research directions based on a systematic literature review, Des. Sci. 10 (2024) e6, https://doi.org/10.1017/dsj.2024.3.
[32] N. Weidmann, S. Salunkhe, A. Anjorin, E. Yigitbas, G. Engels, Automating model transformations for railway Systems engineering, JOT 20 (3) (2021) 10, https://doi.org/10.5381/jot.2021.20.3.a10, 1.
[33] Z. Liu, Q. Chen, N. Xia, M. Yang, Q. Du, J. Lu, An MBSE tool to support architecture design for spacecraft electrical power system, INCOSE Int. Symp 28 (1) (2018) 64–78, https://doi.org/10.1002/j.2334-5837.2018.00468.x. Jul.
[34] F. Dworschak, C. Zirngibl, B. Schleich, S. Wartzack, Konzept für den MBSE-einsatz zur automatisierten individualisierung von komplexen produkten, in: DFX 2019: Proceedings of the 30th Symposium Design for X, 18-19 September 2019, Jesteburg, Germany, The Design Society, 2019, https://doi.org/10.35199/dfx2019.24.
[35] T. Schumacher, R. Stephan, D. Inkermann, Development and implementation of digital heterogeneous models in model-based systems engineering (Status: accepted), in: presented at the 35th CIRP Design 2025 Conference, 2025.