



Aspects of describing product models in engineering design research

Lukas Paehler¹ · Patric Graubeger¹ · Sven Matthiesen¹

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Abstract

Product models are an important part of a designer's daily practice, and as such, they require the continuous attention of design researchers for further progress in support of practice. However, how product models are described in design research, i.e., the aspects used and their structure, is undetermined, although this would provide the basis for developing and using a consistent vocabulary in a structured way. To address this problem, 101 descriptions of product models from the literature were analyzed to identify their underlying aspects. The aspects were then analyzed for statistical relations, which would indicate a structure. The analysis revealed 12 underlying aspects within the descriptions of product models and several relations within them. The identified aspects indicate a gap between the descriptions of product models and the vocabulary available for them, as there is partly no vocabulary for aspects or the existing vocabulary is not reflected in the aspects. Also, the statistical relations indicate individual logical relations between aspects, but a recurring structure in the descriptions is missing. Therefore, the findings were synthesized into a template for describing product models in engineering design research. This proposed template structures the identified aspects according to the objective of the product model description and provides a suitable term for each aspect. Thus, the underlying aspects of descriptions of product models and relations within them could be identified to provide them to design researchers in the form of a template for use during the development and further refinement of product models.

Keywords Design research · Engineering design · Product model · Product modeling · Product representation

1 Introduction

With their wide range of applications in engineering design, models have earned the reputation of being “The Language of the Designer” (Andreasen 1994: 103). Product models (sometimes also referred to as artefact models, see Maier et al. (2014: 139)) are commonly used across product development. A product model is “*a human-made, pragmatic, reductive representation of a technical product carrying attributes similar to the modeled original for the purpose of depicting its function, behavior, or structure, or for analyzing its behavior*” (Paehler and Matthiesen (2024: 289), based on Andreasen et al. (2015), Stachowiak (1973), and Eckert and Hillerbrand (2018)). Examples are the Design Structure Matrix (DSM)(e.g., Browning 2016), Function

Means Tree (e.g., Cao and Fu 2011), Multibody System (e.g., He et al. 2012), and Symbolic Representation (e.g., Andreasen et al. 2015). Through such product models, designers are able to interact with the unfinished product (Eckert et al. 2015).

While the first product models were physical miniatures of the later product, nowadays there are more dedicated product models which have become more abstract, selective, and focused on achieving a particular purpose (Eckert and Stacey 2010). This is due to changes affecting design practice, such as the increasing complexity of technical systems (e.g., Suh 2005; Tomiyama et al. 2007), multi-domain teams and products (e.g., Weidmann et al. 2017), and required modularity (e.g., Baylis et al. 2018). Further changes can be assumed in the future, so the need for adequate product models that can satisfy the expected purpose within the circumstances of the application will continue and affect design research.

The research on product models pursues various objectives. For example, existing modelling approaches are being further developed to open up new application

✉ Lukas Paehler
lukas.paehler@kit.edu

¹ Karlsruhe Institute of Technology (KIT), IPEK – Institute of Product Engineering, Kaiserstr. 10, 76131 Karlsruhe, Germany

scenarios, as can be seen, for instance, in the advancement of the DSM (see Browning 2016). Also, new approaches to building product models are being developed (e.g., Wilschut et al. 2018; Wong and Wynn 2023) and existing product models are integrated into methods (e.g., Alizon et al. 2007; Efrati and Reich 2023). Equally, research into the impact and perception of the use of product models on designers is undertaken (e.g., Gericke et al. 2017). These research activities depend on each other's findings, which are shared through the accompanying descriptions of the product models.

But the vocabulary used in the descriptions of product models in the literature is inconsistent. This can be seen, for example, by comparing the following three excerpts from descriptions of product models:

- “The purpose of representing the bond graph fundamental component as a diagonal matrix is to conveniently conduct design synthesis and search for multi-solutions.” (Cao and Fu 2011: 135)
- “Its aim [of the product model] is to support design engineers in recognizing function-related parameters of the embodiment.” (Grauberger et al. 2020c: 898)
- “The goal of the DSM is to expose the structure of a system's architecture or design.” (Browning 2016: 28)

The excerpts are taken from the descriptions of three product models, all of which can be used during the embodiment design phase to highlight a specific type of relationship within a technical system. Therein, inconsistent vocabulary (each underlined) is used to introduce what is being described. That is, ‘goal’, ‘aim’, or ‘purpose’. Meanwhile, what is being described, the aspect of the product models, is the same across the excerpts. That is, what each product model is intended to be used for. The term ‘aspect’ is used in this article to refer to *a descriptive feature of product models, encompassing their modelling, that can be applied to different product models, modelled technical systems, and applications under consideration*. The example thus shows that inconsistent vocabulary is used for the same aspect of product models.

There are several issues associated with inconsistent vocabulary in the literature. These issues include, for example:

- Outsiders may perceive a lack of consensus, which can affect uptake in practice (Gill 1990).
- A lack of a shared understanding within a domain (Gruber 1993).
- The comparison of techniques and results is hindered (Ullman 1992; Eder 2003).
- Weakened quality and strength of the discourse (Krippendorff 1995).

- Ambiguity, when apparently identical symbols are used with different meanings (Štorga et al. 2010).
- Difficulties in tracking overarching changes and trends in research, as the relationships between the concepts described remain invisible (cf., Cash et al. 2022).
- A limited ability to efficiently communicate research findings to groups outside the research community (cf., Gray 2022).

Such issues have been noted, for example, in the context of modularization (see Bonvoisin et al. 2016) and design methodology (see Hein 1994), but also outside of design, for example, in medicine (see Raebel et al. 2013) and computer science (see Utting et al. 2012). Thus, a lack of a consistent vocabulary hampers researchers' capabilities and the quality of research, including in research on product models.

The vocabularies that could potentially be used consistently and thus shape the discourse in research on product models vary in the aspects of the product models they describe. For example, there is Hubka's (1980) large collection of terminology for the science of design engineering, which has contributed to Buur and Andreasen's (1989) morphology of design modelling, together with the characteristics of modelling by Tjalve et al. (1979). Hubka also influenced Ullman's (1992) taxonomy for mechanical design. Further, some collections are more focused on the application of product models within design processes, for example Kohn et al. (2013) and Lauer et al. (2007). The vocabulary within these collections is partly the same and partly different with regard to the covered aspects. In addition to such collections, there are also ongoing in-depth discussions about individual terms related to product models and their meaning. For example, the persisting discussion about the term function (see Eckert et al. 2011) and granularity (see Maier et al. 2017). As a result of these constant discussions, the vocabulary is constantly changing, expanding, and describing varying aspects of product models. Thus, the aspects of product models to be described in design research remain undetermined in the process.

Furthermore, it remains unclear to what extent certain aspects are logically related, and therefore, should be described together to provide their context. An example of such a relation within the descriptions of product models is their input and output. Buur and Andreasen's (1989) morphology of design modelling characteristics, for example, is divided into the modelling activity and the design model, whereby terms are assigned to one of these two parts, reflecting their relations. A parallel discussion in design research deals with a similar topic, the descriptions of design methods and their structure. Therein, Gray (2022) described three stances regarding design methods, each of which incorporates certain thematically related aspects. These thus represent the aspect's relations for describing design methods

using a consistent vocabulary in a structured way. Yet, despite such discussions, the extent to which such relations between the aspects used to describe product models are reflected in the descriptions in the literature is undetermined. But knowing the relations is necessary to take the context of the aspects into account, the syntax of the descriptions of product models.

In conclusion, the problem is that the aspects of product models to be described in engineering design research, as well as the relations between the aspects, are undetermined, although these would provide the basis for developing and using a consistent vocabulary in a structured way.

2 Contribution of this article

To contribute to solving this problem, this article aims to identify the underlying aspects used to describe product models, and how these aspects are related to each other. This enables a comparison as to how well the aspects actually described and their relations correspond to the vocabulary provided in the state of research and the structures contained therein. Based on the identified aspects and their relations, a template for researchers developing or refining product models is proposed. This template can be used to describe product models in engineering design research and shall be grounded in the existing descriptions in the literature. This may serve as a guide as to what aspects should be considered and described when developing a new product model or further refining an existing one, so that other researchers can acquire all the required aspects with their context to build on or follow up on it. The intended main contribution of this publication is therefore (1) a descriptive understanding of the current practice of describing product models in design research, and (2) the prescriptive transfer of this understanding into an applicable template. This is also what distinguishes this contribution from existing works, such as Buur and Andreasen (1989) or Hubka (1980), which do not provide a descriptive understanding and therefore do not ground their terminology in one traceably. This article thus follows the efforts in other fields, such as medicine (e.g., Raebel et al. 2013) and software development (e.g., Utting et al. 2012), towards more consistent descriptions.

To achieve the stated aim, the following two research questions are formulated:

RQ1: What aspects do the descriptions of product models refer to in engineering design research?

RQ2: How are the aspects referred to in the descriptions of product models related to each other?

With regard to the scope of this article, the term ‘product model’ is used to relate to both the product model and its modelling. This is due to the fact that in the descriptions present in the literature on design research, the two are

inseparably intertwined. For instance, modeling significantly influences what is represented by the technical system in the resulting model (Andreasen 1994). And the purpose, way, and theory of modeling determine the capabilities of the model (Maier et al. 2014). Therein, the purpose of modeling and the purpose of the model are often described synonymously (e.g., Eckert and Stacey 2010). At the same time, there should be no confusion with other terms, such as ‘design methods’. Gericke et al. (2017) describe design methods as specifications of how a certain result is to be achieved, but this result does not have to be a product model. This is evident in ideation methods, for example.

The research questions are answered through a literature review. Section 3 introduces an existing literature collection that was used and explains how it was analyzed to derive the aspects of the descriptions of product models and their relations. Section 4 presents the results in the form of an overview of the underlying aspects of product model descriptions and a table of the relations between the aspects. Section 5 discusses how the aspects align with the vocabulary existing in the literature, their relations, and derives the proposed template. The main conclusions and the outlook are presented in Section 6, follow by the limitations in Section 7.

3 Materials and methods

To answer the research questions, an existing literature collection created by Paehler and Matthiesen (2024) was drawn on, the descriptions of the product models therein were analyzed regarding their aspects according to Wolfswinkel et al.'s (2013) grounded theory based literature analysis (see Section 3.1), and the identified aspects subsequently checked for relations using Fisher’s exact test (see Section 3.2). The steps are described in detail below.

Paehler and Matthiesen (2024) investigated the links between product models in embodiment design, addressing the following research questions: “RQ1: Which categories of similar inputs and outputs of product models in embodiment design can be identified in the literature?” and “RQ2: Which links between product models in embodiment design can be formed based on the inputs and outputs from the literature?” (Paehler and Matthiesen 2024: 291). To compile a literature collection for answering the questions, the literature review by Matthiesen et al. (2019b), which covered publications from 2009 to 2018, was updated to include publications up to 2022, thus covering the entire timeframe from 2009 to 2022. Therein, the systematic literature search according to Dresch et al. (2015) was used. As search terms, *embodiment design*, *embodiment design AND model*, *embodiment design AND analysis*, *embodiment design AND synthesis*, *embodiment function relation*, *function model**, *product model*, and *system* modeling* were used. They were applied to the

databases *ASME digital collection*, *Google Scholar*, *IEEE*, *ResearchGate*, *Scopus*, and *Web of Science*.

Subsequently, three sets of inclusion criteria were applied: The first set of inclusion criteria was applied to narrow down the publications to only include those published within the defined timeframe, in the field of engineering design, and written in English. The second set of inclusion criteria narrowed the publications down to those mentioning a product model or modelling process in the title or abstract, along with keywords indicating the context of embodiment design. Finally, the third set of inclusion criteria considered whether the full text described a product model, specified the type of depiction and the type of information of the model, and that the source is a peer-reviewed journal or conference proceeding. Thereby, a literature collection containing 52 different product models across 72 publications covering the timeframe from 2009 to 2022 was compiled. Therein, both publications in which new product models were presented and publications in which existing product models were described for reuse were included. The product models of the literature collection and their references are provided as part of Table 6 in the appendix.

Despite the focus of the literature collection on the embodiment design phase, it is suitable for this investigation. The embodiment design phase is described by Pahl and Beitz (1996: 199) as “that part of the design process in which, starting from the working structure or concept of a technical product, the design is developed, in accordance with technical and economic criteria and in the light of further information, to the point where subsequent detail design can lead directly to production [...]”. The included product models contain, for example, the “concept model graph” according to Muenzer and Shea (2017), the “function structure” according to Chakrabarti et al. (2011), the CAD model, and FEM model according to Danjou et al. (2008). Still, these product models’ use is not limited to the embodiment design phase. Hence, although the literature collection is focused on the embodiment design phase, it contains product models that are used across multiple phases of the product development process, making it a suitable sample for the analysis in this contribution.

3.1 Analysis of the publications with regard to the aspects of the product model descriptions

The publications of the literature collection were analyzed using the grounded theory based literature analysis according to Wolfswinkel et al. (2013), which is based on grounded theory according to Glaser and Strauss (1967). This analysis was used because it is intended to provide insights into textual contents that initially appears to be independent and to

establish a relationship between it, which corresponds fully to the aim of this contribution.

The analysis was carried out in the MindManager software.¹ In the analysis, when considering a publication, there may be several descriptions of product models in it, as some publications contain and describe multiple product models. These were counted as individual descriptions, resulting in more descriptions than publications. For each individual description, excerpts were first extracted from the publications that describe the product model under consideration, i.e., words, sentences, or paragraphs. The excerpts were sorted based on the publications and described product models. This could later be used to trace which aspects were described in which publications (see Table 6 in the appendix).

This was followed by the coding procedure according to Wolfswinkel et al. (2013). The coding procedure is subdivided into ‘open coding’, ‘axial coding’, and ‘selective coding’. “[...] open coding is the analytical process of generating higher-abstraction level type categories from sets of concepts/variables. Axial coding is the further developing of categories and relating them to their possible sub-categories. With selective coding the categories are integrated and refined.” (Wolfswinkel et al. 2013: 7) In the context of this study, the concepts/variables were the excerpts of product model descriptions from the publications. The categories were the aspects in the form of descriptive questions, which could be, for example, “How is the content of the product model represented?”. Such descriptive questions were used to (1) enable a comparison of the identified aspects with existing terms from the literature later in the discussion which would otherwise be prevented, and (2) lay the basis for the template that is to be proposed subsequently which shall provide researchers with easily applicable aid when describing product models. These were consolidated in an overview.

Figure 1 shows an example of how four excerpts from publications are analyzed to achieve an aspect through the coding steps. On the left are examples of text excerpts from publications, and to the right is how these are initially consolidated into three preliminary aspects in open coding. These are then summarized into one aspect in axial coding, which does not change further in the selective coding step.

The coding steps were performed in the order described, starting with open coding of all excerpts, then moving on to axial coding, and finally performing selective coding. Initially, one of the authors carried out all the steps. The preliminary results were then evaluated and refined during

¹ For more information on MindManager, see <https://www.mindmanager.com/en/>

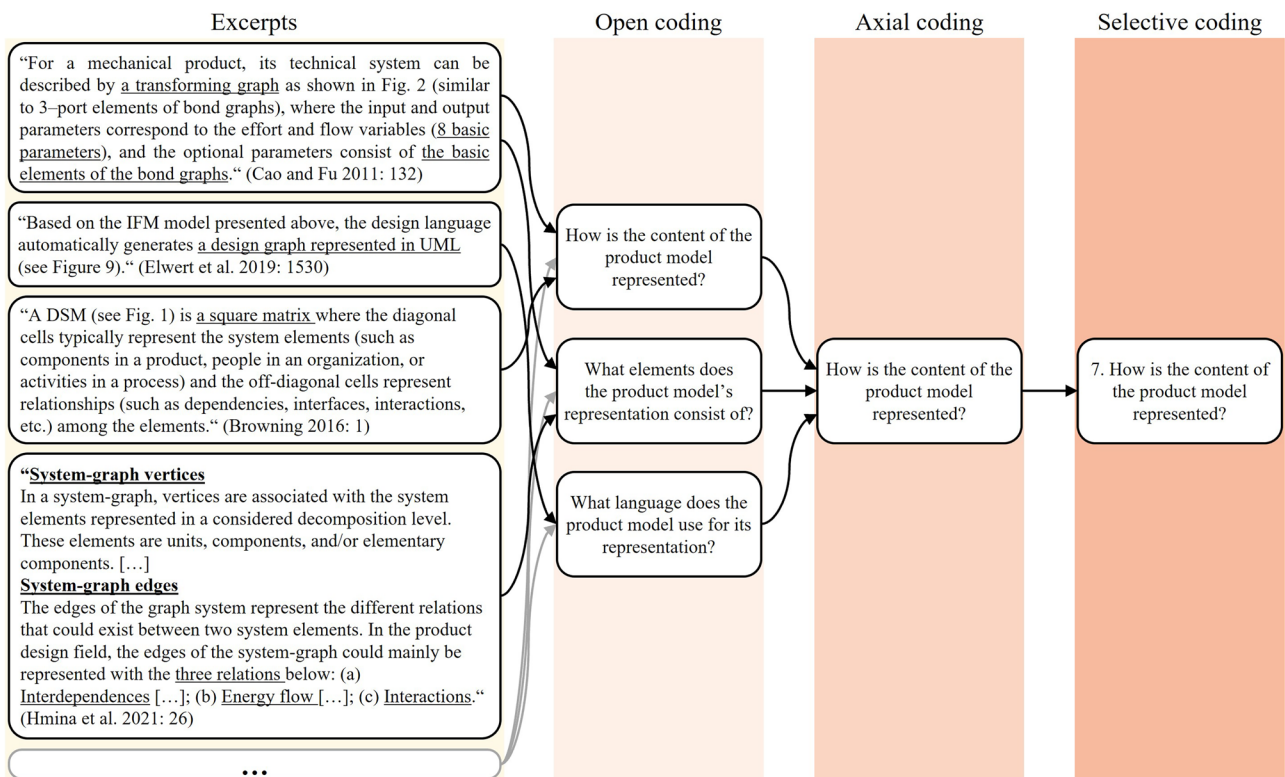


Fig. 1 An example demonstrating the coding steps from excerpts from the publications to the aspect resulting from the completed selective coding. The segments of the excerpts relevant to the coding are underlined

a structured review session with independent researchers to produce a final, consistent set of aspects.

Thus, the analysis resulted in an overview of the consolidated aspects of the product model descriptions found in the publications in the form of descriptive questions, answering RQ1: “What aspects do the descriptions of product models refer to in engineering design research?”.

3.2 Statistical analysis of the aspects to determine their relations

The analysis described in Section 3.1 provided the aspects of the product models and the publications in which they appear. Thus, for each combination of two aspects, it was subsequently determined how often none, one, or both of the aspects were described across all publications. This could be represented as a 2 × 2 contingency table for each combination of two aspects. Consider aspect X and aspect Y, the fields within the table indicate whether X and Y occur together, whether X occurs without Y, whether Y occurs without X, and whether neither aspect occurs. Since it was expected that some aspects would occur only rarely, Campbell's (2007) recommendation was followed and Fisher's exact test was used for the statistical analysis instead of the chi-squared test. Fisher's exact test can also be used for

such smaller samples (Yates 1934). It was therefore used to investigate whether there are statistically significant relations between the occurrences of the aspects of the product model descriptions. I.e., whether certain aspects tend to be described in combination or that they are not. This was statistically investigated, as combinations of aspects that are jointly described for their context, or a recurring syntax, would show up in it.

The statistical tests were carried out in IBM SPSS Statistics.² Fisher's exact test was applied to the contingency tables of all possible combinations of aspects. The significance level for the test was set at $p=0.05$. If a statistical relation was identified through Fisher's exact test, the Phi coefficient was additionally used to determine the direction of the relation. Therein, a relation could be positive, meaning that the aspects tended to occur together in publications, or negative, meaning that the aspects did not tend to occur together within publications. From these statistical tests, a table was obtained in which the result of Fisher's exact test is shown for each combination of aspects as an assessment

² For more information on IBM SPSS Statistics, see <https://www.ibm.com/products/spss-statistics>

of the relation, supplemented by the Phi coefficients for the identified statistically significant relations.

Thereby, the relations of the aspects referred to by the product model descriptions were derived, answering RQ2: “How are the aspects referred to in the descriptions of product models related to each other?”.

4 Results

The results are structured according to the research questions: First, answering research question 1, the identified aspects of the product model descriptions are presented as the result of the grounded theory-based analysis; second, the relations between the identified aspects are presented as the result of the statistical tests and thereby answer to research question 2.

4.1 The aspects of product model descriptions

As more than one product model was described in several publications, the 72 publications in the literature collection resulted in a total of 101 descriptions of product models. From these, the excerpts were extracted. In the subsequent coding process, 19 aspects were initially abstracted across the descriptions through open coding. During axial coding, these were narrowed down to 12 aspects referred to in product model descriptions. The selective coding did not lead to a change in the number of aspects. As a result and answer to research question 1, 12 aspects to which the descriptions of product models refer were derived. The aspects are listed in Table 1 with examples. The table is sorted thematically so that aspects relating to the application are listed first, then aspects relating to the representation, and finally aspects relating to the modelling. In addition, Table 2 shows how often the aspects appeared within the 101 descriptions of product models.

Table 6 in the appendix lists which aspects were identified in which publication, sorted by product model. Also, the MindManager file, in which the excerpts from the publications describing the product models and the coding steps are documented and can be retraced, is attached as supplementary material.

4.2 The relations within the aspects of product model descriptions

The results of Fisher's exact test are shown in Table 3. A statistically significant relation was found for seven combinations of aspects – these are marked with a * in the table and answer research question 2. The Phi coefficients of the statistically significant relations show that three of the relations are negative, meaning that the aspects do not tend to occur together.

The sample is consistently at $n=101$, the number of descriptions of product models. The significant negative relations are between the aspects:

- **1** “What is the product model used or intended to be used for?” and **12** “Which other product model(s) can be built from the given product model?” ($p=0.002$, $\varphi=-0.299$);
- **6** “What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?” and **8** “Which data, information, knowledge, or other product model is used as the basis for building the product model?” ($p=0.001$, $\varphi=-0.346$); and
- **7** “How is the content of the product model represented?” and **8** “Which data, information, knowledge, or other product model is used as the basis for building the product model?” ($p=0.048$, $\varphi=-0.206$).

According to Cohen (1988), the effect size between aspects **6** “What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?” and **8** “Which data, information, knowledge, or other product model is used as the basis for building the product model?” is medium and the other effect sizes are weak. The other four combinations show significant positive relations, indicating that the aspects tend to occur together. The significant positive relations are between the aspects:

- **2** “When is the product model used or intended to be used within a design process?” and **9** “How is the product model build?” ($p=0.001$, $\varphi=0.371$);
- **2** “When is the product model used or intended to be used within a design process?” and **5** “What limitations need to be considered when using the product model in a design process?” ($p=0.034$, $\varphi=0.243$);
- **3** “How is the product model technically integrated into a design process?” and **9** “How is the product model build?” ($p=0.045$, $\varphi=0.241$); and
- **6** “What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?” and **7** “How is the content of the product model represented?” ($p=0.004$, $\varphi=0.295$).

According to Cohen (1988), the effect size between the aspects **2** “When is the product model used or intended to be used within a design process?” and **9** “How is the product model build?” is medium, and the other effect sizes are weak.

Table 1 Overview of the aspects referred to in the product model descriptions with examples. The segments of the examples to which the aspects refer are underlined

Aspects	Examples
1 What is the product model used or intended to be used for?	<p>“[...] the axiomatic design model is utilized to <u>guide and verify that the top-level design is either an uncoupled or a decoupled design.</u>” (Leu et al. 2009: 149)</p> <p>“The approach aims at <u>converting the function models to a list of governing equations and a causal graph between the variables in the system.</u>” (Mokhtarian et al. 2017: 477)</p> <p>“This well-defined arrangement has proved to be particular useful for <u>computational analysis methods.</u>” (Bonev et al. 2015: 7)</p>
2 When is the product model used or intended to be used within a design process?	<p>“The C&C²-Approach is a thinking tool for <u>embodiment design.</u>” (Matthiesen et al. 2019a: 1485)</p> <p>“[...] can be applied to most of constraint satisfaction problems encountered <u>in the embodiment and detailed design phase</u> of mechanical systems design.” (Dantan et al. 2013: 148)</p> <p>“<u>During the conceptual and embodiment design,</u> product developers often use sketches or models to generate solutions.” (Seybold and Mantwill 2021: 2)</p>
3 How is the product model technically integrated into a design process?	<p>“[...] which is often compatible and highly <u>integrated with the PLM System.</u>” (Aranburu et al. 2022: 384)</p> <p>“Additional information, <u>such as attributes, external documents, and models of different kinds, can be linked to the objects in the EF-M model.</u>” (Müller et al. 2019b: 509)</p>
4 What is the foundation (e.g., paradigm, theory, principle, etc.) on which the product model is based?	<p>“CAD systems have been employed since the 1980s, and the most widely used rely on <u>feature-based associative parametric technology [2,4].</u>” (Aranburu et al. 2022: 384)</p> <p>“<u>Bond graph theory</u> provides a compact list of those elementary bricks (Karnopp et al., 2012).” (Mokhtarian et al. 2017: 482)</p> <p>“CPM is mainly based on <u>the distinction between characteristics (in German: “Merkmale”) and properties (“Eigenschaften”) of a product: [...].</u>” (Weber 2005: 162)</p>
5 What limitations need to be considered when using the product model in a design process?	<p>“<u>A lack of consistent modelling practices, the complexity of relations in a master model and ambiguous feature definitions make CAD models difficult to edit and lead to failures in their regeneration [20,21,23].</u>” (Müller et al. 2020: 3)</p> <p>“Created models become <u>incomprehensible and are no longer helpful, when EFRs [embodiment function relations] have to be considered on different levels of detail in different states of the system</u> which is often the case in complicated systems.” (Matthiesen et al. 2019a: 1484)</p> <p>“In order for this model to be a good approximation of the real compliant mechanism, <u>a series of conditions must hold: [...].</u>” (Berselli et al. 2016: 1210)</p>
6 What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?	<p>“CAD models are a representation of <u>a product’s geometry and topology.</u>” (Müller et al. 2020: 3)</p> <p>“[...] <u>which sub-systems, alone or in combination with others, are foreseen for implementing the different functions</u> that the system is expected to fulfil.” (Eisenbart et al. 2017b: 313)</p> <p>“[...] <u>the input and output relations</u> in a mechanical system can be described [...]” (Cao and Fu 2011: 132)</p>
7 How is the content of the product model represented?	<p>“A classical bond graph model is expressed via <u>a set of nine elementary elements. The nine elements are as follows: [...].</u>” (Mokhtarian et al. 2017: 485)</p> <p>“[...] can be described by the following <u>matrix equation: [Output parameter]=T [Input parameter][...]</u> Where, T is the so-called the behavioral matrix.” (Cao and Fu 2011: 133)</p> <p>“A CMG [concept model graph] is, as the name suggests, <u>a graph. It consists of two parts: [...].</u>” (Muenzer and Shea 2017: 3)</p>

Table 1 (continued)

Aspects	Examples
8 Which data, information, knowledge, or other product model is used as the basis for building the product model?	<p>“[...] automatically generates the CAD models of all technically feasible concepts captured in <u>the EF-M model</u>.” (Müller et al. 2020: 5)</p> <p>“[...] a bond-graph-based simulation model that is generated from the <u>CMG [concept model graph]</u>.” (Muenzer and Shea 2017: 3)</p> <p>“Based on <u>the IFM model</u> presented above, the design language automatically generates a design graph represented in UML (see Fig. 9).” (Elwert et al. 2019: 1530)</p>
9 How is the product model build?	<p>“The <u>general steps to construct geometry in a parametric CAD system</u> were summarized by Hartman [7] as shown in Table 1.” (Aranburu et al. 2022: 384)</p> <p>“To build up C&C2-Models, a <u>seven-step method</u> is presented in the chapter on embodiment design in Pahl and Beitz [36]. <u>This method is described in the following: [...]</u>” (Grauberger et al. 2020b: 6)</p> <p>“Eppinger and Browning (2012) introduced a <u>five-step DSM method to architectural modeling and analysis</u>, as depicted in Fig. 2.” (Wilschut et al. 2018: 532)</p>
10 How can the product model be modified?	<p>“This needs designer to add the behavioral matrix into the system and/or <u>decompose the original transforming matrix further</u> until the basic mechanical components.” (Cao and Fu 2011: 140)</p> <p>“The guideline includes <u>the following activities, which can be repeated in a process of iterative convergence: [...]</u>” (Albers et al. 2009: 4)</p>
11 What data, information, or knowledge can the product model provide?	<p>“By analyzing the causality and nature of each bond graph element, we extracted <u>the list of possible functions in Table 1</u>.” (Mokhtarian et al. 2017: 485)</p> <p>“The connectivity graph provides <u>information about existence of connection between the components as well type of connection between the components</u> in a product.” (Ameri et al. 2008: 170)</p> <p>“As will be illustrated further down, what this effectively means is that, for every process, the state view will provide <u>the states and their changes related to it</u>.” (Elwert et al. 2022: 7)</p>
12 Which other product model(s) can be built from the given product model?	<p>“Using the predefined causality rules for each bond graph element (see Fig. 11), <u>a general causal graph and the governing equations</u> are generated.” (Mokhtarian et al. 2017: 495)</p> <p>“From this central meta- or system model, <u>further models (for example CAD geometry models, simulation models like FEM or multi-body-system, MBS, reports, etc.)</u> can be generated in a fully automatic manner.” (Elwert et al. 2019: 1526)</p> <p>“<u>Clustered DSM</u> to compare different modularisation of two variants created from information stored in the EF-M model.” (Müller et al. 2019a: 1428)</p>

Table 2 Count of occurrences of the aspects referred to in the product model descriptions. The aspects are numbered according to Table 1

Aspect	1	2	3	4	5	6	7	8	9	10	11	12
Count	47	12	5	28	12	74	68	24	19	2	15	13

5 Discussion

Analogue to the results section, the discussion is structured according to the research questions and thus begins

with the aspects of the product model descriptions, followed by their relations. Thereafter, the findings are synthesized into a proposed template for describing product models in engineering design research.

Table 3 Relations (p-values) between the occurrences of the aspects according to Fisher’s exact test. The aspects are numbered according to Table 1

Aspect	1	2	3	4	5	6	7	8	9	10	11	12
1	-											
2	0.217	-										
3	0.059	0.476	-									
4	0.504	0.733	0.615	-								
5	0.539	0.034*	0.476	0.305	-							
6	0.121	1	0.321	0.616	0.729	-						
7	0.672	0.199	0.661	0.352	0.055	0.004*	-					
8	0.063	0.726	1	0.069	1	0.001*	0.048*	-				
9	1	0.001*	0.045*	0.777	0.232	0.091	1	0.230	-			
10	0.214	0.225	1	1	1	1	1	1	0.342	-		
11	1	0.205	0.560	0.550	0.688	0.538	0.557	0.750	1	1	-	
12	0.002*	0.356	0.505	0.751	0.356	0.743	0.753	0.074	0.453	1	1	-

Aspect 10 only appears twice in the analyzed product model descriptions. This limits the meaningfulness of the statistical tests with this aspect.

* $p < 0.05$.

5.1 The aspects of product model descriptions

For the consideration of the aspects within the state of research, the identified aspects are listed in Table 4 with the terms from the literature with which they can be described. Therein, publications that include a broad timeframe and specify terms to describe models were included. As Table 4 shows, 11 of the 12 aspects can be found in the vocabulary in the literature. A further distinction can be made between aspects that are frequently or only rarely reflected in the literature. Aspects 1 “What is the product model used or intended to be used for?”, 6 “What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?”, and 7 “How is the content of the product model represented?” are frequently found. This is in line with the analysis of the aspect per publication (see Table 2). The analysis shows that these three aspects are the most frequently described aspects across the publications. The aspects that are only rarely reflected in the literature on terms for describing product models also occurred less frequently in the analysis of aspects per publication. Thus, the reflection of aspects in publications on vocabulary and the occurrence of the aspects in publications with descriptions of product models coincide.

In the publications on terms for describing product models included in Table 4, aspect 3 “How is the product model technically integrated into a design process?” is not included. A clarification of whether aspect 3 is distinct from the aspects that are included in the publications on terms for describing product models in Table 4 is necessary at this point: Aspect 3 differs from aspect 2 “When is the product model used or intended to be used within a design process?” in that aspect 2, as shown in the examples in Table 1, describes an intended time of use, whereas aspect

3 describes the technical integration, which may also extend beyond the intended time of use. Aspects 8 “Which data, information, knowledge, or other product model is used as the basis for building the product model?” and 11 “What data, information, or knowledge can the product model provide?”, on the other hand, describe the data, information, knowledge, or other product model that can be used for building or are provided by the described product model. However, how these are technically implemented is not necessarily described, which is particularly evident in the examples of aspect 11 in Table 1. While aspect 3 is thereby clearly distinct, it is not entirely clear why aspect 3 is so rarely described and not reflected in the literature. A possible explanation could be that the description of product models often focuses on the description of the individual and thereby isolated product models, and therefore, the technical integration into a design process is given a subordinate role. This could be the case due to researchers considering the integration as a task for developers of software tools for design. An alternative explanation could be that the integration is regarded by the researchers as natural due to the context of the publication and is therefore not explicitly described. As such, there is a need to further investigate the aspect in the context of the vocabulary for product model descriptions.

In publications on the vocabulary of product models, though, aspects are also described that were not identified in the publications analyzed in this investigation. Maier et al. (2014) and Tjalve et al. (1979), for example, consider the model user and discuss in this context that the user of a model does not necessarily have to be the person who built the model. Tjalve et al. (1979), Buur and Andreasen (1989), Andreasen et al. (2015), and Lauer et al. (2007) also consider the medium on which the product model

Table 4 Existing terms from the literature for the identified aspects

Aspects	Terms for the identified aspects				
	Tjalve et al. (1979)	Hubka (1980)	Buur and Andreasen (1989)	Kohn et al. (2013)	Andreasen et al. (2015)
1 What is the product model used or intended to be used for?	Use	Purpose	Purpose	Purpose	Purpose
2 When is the product model used or intended to be used within a design process?			Stage of design	Timetable	
3 How is the product model technically integrated into a design process?					
4 What is the foundation (e.g., paradigm, theory, principle, etc.) on which the product model is based?		Principle			Theory <i>or</i> vision <i>or</i> way of modelling
5 What limitations need to be considered when using the product model in a design process?				Requirements	
6 What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?	Modelled properties	Property of the technical system	Modelled properties		Attributes
7 How is the content of the product model represented?	Code	Code	Code <i>or</i> modelling language	Modelling language	Code
8 Which data, information, knowledge, or other product model is used as the basis for building the product model?		Input		Previous knowledge	
9 How is the product model build?					Modelling
10 How can the product model be modified?					Modelling
11 What data, information, or knowledge can the product model provide?		Output			
12 Which other product model(s) can be built from the given product model?		Coupling		Relation	

is present and can be exchanged between people and/or systems. And likewise, Andreasen et al. (2015), Hubka (1980), and Maier et al. (2017) consider the abstraction level of product models. The fact that these aspects are not found in the descriptions of the product models indicates that there is a gap between the aspects of product models discussed in design research and the product model's description, or that the objective with which product

models are described in research does not recognize the need for these aspects.

In summary, there are aspects such as **1** „What is the product model used or intended to be used for?“, **6** „What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?“ and **7** „How is the content of the product model represented?“ that are frequently found in publications on vocabulary for product

models as well as in the publications in which product models are described. At the same time, there are also aspects with a gap between the descriptions in publications and the available vocabulary, i.e., aspect 3 “How is the product model technically integrated into a design process?” which is not found in the publications on terms for describing product models as well as the lack of aspects relating to the model users, the medium and abstraction.

5.2 The relations within the aspects of product model descriptions

The statistical relations between the combinations of contents of the descriptions of product models in Table 3 show that there is a significant correlation in only seven of the 66 combinations of aspects. These relations reveal which aspects are frequently used together within the same description and which aspects rarely appear in the same description of a product model. Given that researchers deliberately choose how they describe product models and therein which aspects to describe together or not, the following paragraphs provide a possible explanation for the cause for these relations.

In the positive relations of aspects, the combinations appear logical. For instance, aspect 6 “What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?” is logically related to aspect 7 “How is the content of the product model represented?” as they both relate to the representation and are also mentioned in the same sentence in several publications. These relations therefore indicate that a syntax has emerged within product model descriptions, in which aspects are brought together. Similarly, the relation between aspect 2 “When is the product model used or intended to be used within a design process?” and aspect 9 “How is the product model build?” and 5 “What limitations need to be considered when using the product model in a design process?” is retrospectively plausible, as these aspects can be used to describe the application of a certain product model within a design process, i.e., when, how and under what conditions its can be used. Therein, why certain aspects are described together can be explained by the objectives of the description being similar and thereby bringing them together. Hence, these relations point to possibilities that researchers can use in their descriptions to employ similar structures, which in turn contribute to consistency.

By contrast, the explanation of the negative relations is vaguer. For example, the relations between the aspects 8 “Which data, information, knowledge, or other product model is used as the basis for building the product model?” and the aspects 6 “What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?” and 7 “How is the content of the product model

represented?” are noticeable as the information with which a product model is build is not described in common with either how or what is represented which detaches the representation of a product model from its building process. A possible explanation for this could be that these aspects are not described together, as these aspects are each being used in the context of a description with a particular objective. This would mean that the aspects do not exclude each other in terms of meaning, but that the researchers did not need to describe them together in the respective contexts. While aspects 6 and 7 focus on representational aspects, aspect 8 focuses on functional aspects. Hence, together with the positive relations, this indicates that there are logical combinations of aspects for describing product models that are also linked to the objectives of the descriptions.

In summary, the relations suggest that describing product models with similar objectives also leads to the consideration of the same aspects. Likewise, different objectives may lead to the description of different aspects. Further, the relations indicate that content-related similarities like the representation can lead to the joint description like a syntax. With regard to a more consistently used vocabulary, the relations can therefore be used as an initial point of reference for creating recognizable structures within the description so that researchers can find related aspects together.

5.3 The proposed template for describing product models in engineering design research

To make the findings from research questions 1 and 2 more easily usable, they are synthesized into a proposed template for describing product models for researchers developing or refining product models. This is shown in Table 5.

The discussion of research question 2 indicates that different objectives for describing product models require different aspects. Accordingly, it is not necessary to always describe all aspects. Based on the relations and meanings of the aspects, they are structured according to three objectives for describing product models: usage, representation, and functionality. This structure takes into account the identified positive and negative relationships, with the exception of the relationship between aspects 2 “When is the product model used or intended to be used within a design process?” and 9 “How is the product model build?”. This is neglected in favor of a clear separation of different objectives. The relations are incorporated into the structure to ground the template in the existing descriptions of product models in the literature. The identified relations represent statistically significant joint or separate occurrences of aspects. As explained in the discussion in Section 5.2, this can be explained by the different objectives for which product models are described. By incorporating the relations into the template, the way in which product models are described

Table 5 The proposed template for describing product models in engineering design research divides the aspects according to three objectives and links them to suitable terms

Objective of the description	Aspects to consider	Terms to relate to the aspects
The usage of the product model within a design process	1 “What is the product model used or intended to be used for?”	Purpose (based on Hubka 1980; Andreasen et al. 2015)
	2 “When is the product model used or intended to be used within a design process?”	Stage/phase of design (based on Buur and Andreasen 1989)
	5 “What limitations need to be considered when using the product model in a design process?”	Requirements (based on Kohn et al. 2013)
The representation of the product model	6 “What attributes of the technical system (e.g., geometry, function, etc.) are represented in the product model?”	Modelled attributes (based on Andreasen et al. 2015)
	7 “How is the content of the product model represented?”	Modelling language (based on Buur and Andreasen 1989; Kohn et al. 2013)
	4 “What is the foundation (e.g., paradigm, theory, principle, etc.) on which the product model is based?”	Principle (based on Hubka 1980)
The functionality of the product model	3 “How is the product model technically integrated into a design process?”	Integration (based on Eisenbart et al. 2017a)
	8 “Which data, information, knowledge, or other product model is used as the basis for building the product model?”	Input (based on Hubka 1980)
	9 “How is the product model build?”	Creating (based on Andreasen 1994; Maier et al. 2014)
	10 “How can the product model be modified?”	manipulating (based on Maier et al. 2014; Eckert and Hillerbrand 2022)
	11 “What data, information, or knowledge can the product model provide?”	output (based on Hubka 1980)
	12 “Which other product model(s) can be built from the given product model?”	succeeding model (based on the analyzed descriptions)

so far is adopted rather than prescribing a different or even contradictory way.

Several aspects have to be taken into account for each of the three objectives mentioned. In order to describe these consistently, a suitable term from the state of research is assigned to each of them based on the discussion of research question 1. These are listed in Table 5 on the right, including the references on which they are based / from which they originate. The emphasis was placed on ensuring that the terms accurately reflect the aspect in question and are clearly distinguishable from other terms within the template.

This template is therefore intended to contribute to a more consistent description of product models in design research, meaning that they are described using the same aspects and terminology. This should, among other things, help to make product models as research results more easily accessible and comparable, addressing the issues associated with inconsistent vocabulary (see listing in Section 1). It can therefore be used both during the development of new product models and during further refinements.

The need for new models is motivated by new requirements for technical systems, such as the increased

requirements for circular design. During the development of these product models, the template can be used as a guide to determine which aspects of the new product model need to be considered and specified for a comprehensive description. In this way, communication with other researchers is given consideration during the development as the template can be easily provided as part of the appendix of publications. In addition, the template can also be used for comparison with existing product models. By describing an existing product model that may raise concerns regarding novelty using the template and placing the new product model alongside it, the differences and similarities between the two product models can be easily and quickly assessed.

When further refining existing product models, using the template offers a chance to make trends and evolutions easier to follow. Similar to the development of new product models, the template can be used to describe several generations of the product model as a way to highlight the differences between these generations. Across several refinements, this creates a sequence of templates that can be assembled and compared. When a product model is not refined but rather used in a new context or use case, resulting

changes to aspects such as a new purpose (aspect 1) or lifted requirements (aspect 5) may also be indicated. Furthermore, the templates of different product models can be compared with each other to identify potential links between them, i.e., ways to exchange information between them. Revealing such links can increase the interaction between product models in the state of research, and thereby contribute to their refinement.

In summary, the proposed template brings together the identified aspects and structures them according to three objectives. For each aspect, a suitable term from the current state of research is recommended. The template thus offers a way to contribute to a more consistent vocabulary for describing product models, emerging from the existing descriptions of product models. Simultaneously, the aspects can be used as a guide for each objective, indicating what should be described about a product model when the usage, representation, or functionality is to be presented.

6 Conclusion and outlook

By analyzing publications in which product models were described in engineering design research, 12 underlying aspects were identified to which the descriptions refer (see Table 1). Of these, on the one hand, some aspects occur equally frequently in the descriptions and the vocabulary in the literature, e.g., “What is the product model used or intended to be used for?”. On the other hand, there are aspects for which a gap between the descriptions and the vocabulary in the literature was recognized, as no vocabulary is available for the aspects, or the existing vocabulary is not reflected in the descriptions. An example for such an aspect is “How is the product model technically integrated into a design process?”. The described aspects and the available vocabulary therefore in some cases still diverge.

Examining the identified aspects for relations (see Table 3) indicated that there are aspects that tend to occur together, due to their content-related relations. Equally, some aspects usually occur separately from each other, which can be explained by different objectives of the descriptions of product models. Thereby, a dependency between the aspects described and the objective of the product model description is assumed.

These findings were synthesized in a template for describing product models in engineering design research (see Table 5). This proposed template structures the aspects according to three objectives: usage, representation, and functionality. Therein, a suitable term from the literature is recommended for each aspect. Thereby, the template can be used by design researchers when describing product models, as a guide when developing new product models, or when further refining existing product models.

The main contribution is therefore that the identified aspects and their relations have been synthesized into a template that can be used by researchers who are developing new or further refining existing product models. This template is grounded directly in current practice in the description of product models in design research.

In terms of future research, the gap between the aspects described and the available vocabulary should be addressed in particular. This would lay the foundation for a consistent vocabulary and its use in design research. In addition, closing the gap would bring together the researchers who develop product models and the researchers who deal with the vocabulary. Also, by discussing how the use of a consistent vocabulary for the aspects can be achieved, a progression towards increased comparability, traceability, and transparency of product model descriptions could be achieved in the long term.

7 Limitations

The limitations of this work relate in particular to the range of the publications considered during the analysis, as well as the scope of applicability of the findings, especially the template.

The publications examined originate from a literature review on product models in embodiment design. Although these product models are used throughout larger parts of a product development process, as described in Sect. 2, an increased focus on embodiment design can not be excluded. In addition, the publications examined cover a period of 14 years between 2009 and 2022. During this period, there were also product models that weren't included in the sample investigated due to the databases, search terms, and inclusion criteria used. Similarly, product models developed outside the period under consideration are missing. Both of these points result in the fact that ‘only’ a sample of 72 publications on product models was included in the analysis and its findings.

As can be seen from Table 2, certain aspects already occur frequently in this sample, so it can be assumed that the common aspects have been identified and taken into account. Rarely occurring aspects, especially if they are only occasionally described in product models that are specific to a different phase in product development, may not be represented. In this way, aspects comparable to aspect 10, which only appeared twice in the 72 publications considered, could be missing. As a consequence, the completeness of the aspects can not be determined, however the identified aspects would not be affected by future extensions.

Appendix 1

With regard to the findings, the applicability of the aspects and template is limited to product models like the ones included in the analysis. In particular, it should be ensured that the understanding of what a product model is and its role in a design process is identical with the understanding laid out in the introduction. Further investigations would be required to determine the applicability of the findings, and in particular of the template, prior to the use regarding product models outside of this understanding or engineering design.

With regard to the scope of the template, it must also be noted that, although it divides aspects according to the objective of the description and suggests terms to relate to the aspects, different terminology and levels of detail may still occur within the description of the aspects in design research. I.e., two researchers describing “What is the product model used or intended to be used for?” can still use varying degrees of detail and use different terms. Thereby, the template has no effect or applicability at levels of detail below the specified aspects and therefore delivers no added value in this regard.

See Table 6.

Table 6 Overview of the product models and their references from the literature collection by Paehler and Matthiesen (2024) with the included aspects of the product models. The aspects are numbered according to Table 1

Product models	References	Included aspects											
		1	2	3	4	5	6	7	8	9	10	11	12
2D/3D CAD Models	Aranburu et al. (2022)		x	x	x	x	x			x			
	Eifler and Howard (2018)								x				
	Favi et al. (2021)											x	
	Grauberger et al. (2021)	x				x						x	
	Müller et al. (2020)				x	x	x	x	x				
	Vlah et al. (2021)	x	x			x			x	x			
Allocation Matrix	Eisenbart et al. (2017b)	x					x	x		x			
Axiomatic Design Model	Leu et al. (2009)	x			x			x					
Behavioral Matrix	Cao and Fu (2011)	x					x	x			x		
Bond Graph Model	Cao and Fu (2011)						x	x					
	Mokhtarian et al. (2017)				x		x	x			x	x	
	Muenzer and Shea (2017)				x			x	x				
Causal Graph	Mokhtarian et al. (2017)	x					x		x			x	
Concept Model Graph	Muenzer and Shea (2017)	x					x	x					
Connectivity Graph	Ameri et al. (2008)	x					x	x				x	
C&C ² -Model	Albers et al. (2009)	x	x				x	x		x	x		
	Albers et al. (2019)	x				x	x	x					
	Boersting et al. (2008)	x			x		x						
	Freund et al. (2015)				x		x	x					
	Gladysz and Albers (2018a)	x			x		x	x					
	Gladysz and Albers (2018b)						x	x					
	Gladysz et al. (2018)	x					x	x					
	Grauberger et al. (2022)	x						x					
	Grauberger et al. (2020c)	x	x			x	x			x			
	Grauberger et al. (2021)	x	x		x		x	x		x			
	Grauberger et al. (2020a)	x					x	x					
	Grauberger et al. (2020b)		x					x		x			
	Grauberger et al. (2020d)	x			x		x	x		x			
	Matthiesen et al. (2019a)	x	x		x	x	x	x					
	Wettstein et al. (2021)	x					x	x		x			
	Zingel et al. (2012)	x			x	x	x	x					
Context Object Diagram	Leu et al. (2009)						x						

Table 6 (continued)

Product models	References	Included aspects											
		1	2	3	4	5	6	7	8	9	10	11	12
Characteristics Properties Model	Dantan et al. (2013)	x	x		x			x					
	Köhler (2009)	x			x			x					
	Weber (2005)				x			x					
Design Graph	Elwert et al. (2019)							x	x				x
	Elwert et al. (2022)							x	x				x
Design Structure Matrix	Bonev et al. (2015)	x			x		x	x					
	Browning (2016)	x			x		x	x					
	Eppinger and Browning (2012)	x					x	x		x		x	
	Wilschut et al. (2018)						x	x		x		x	
Digital Mock-Up	Danjou et al. (2008)								x				
	Riascos et al. (2015)	x			x		x						
Enhanced Function-Means Model	Müller et al. (2019b)			x			x	x		x			
	Müller et al. (2019a)				x		x					x	x
	Müller et al. (2020)				x		x	x					
Feature-Based Functional Model	He et al. (2013)				x			x					x
	He et al. (2015)											x	
Feature-Based Effect Model	He et al. (2013)						x	x	x				x
Feature-Based Physical Quantity Model	He et al. (2013)						x	x	x				x
Feature-Based Working Principle Model	He et al. (2013)			x			x	x	x				x
Feature-Based Structure Concept Model	He et al. (2013)							x	x			x	
FEM Simulation Model	Danjou et al. (2008)								x				
	Rajaguru et al. (2010)	x							x			x	
Functional Sketch	Gu et al. (2012)			x			x	x				x	
Function Analysis Diagram plus	Atherton et al. (2018)				x		x	x	x				
Function-Effort-Matrix	Albers et al. (2019)	x					x		x			x	
Function Means Tree	Cao and Fu (2011)				x		x	x		x			x
	Nagel et al. (2008)						x	x					
Function Structure	Ameri et al. (2008)	x					x	x	x				
	Chakrabarti et al. (2011)												x
	Gericke and Eisenbart (2017)							x					
	He et al. (2015)						x	x					
	Mokhtarian et al. (2017)						x						x
	Wökl and Shea (2009)						x	x					
Function Tree	Boersting et al. (2008)				x	x	x			x			
	Leu et al. (2009)						x	x		x			
High Order Object Model	Leu et al. (2009)						x						
Integrated Function Model	Elwert et al. (2019)	x					x	x		x			
	Elwert et al. (2022)	x			x		x	x				x	
	Gericke and Eisenbart (2017)						x	x					
Kinematic Function Model	He and Huang (2016)						x	x					
Kinematic Model	Gao et al. (2015)			x			x	x					
Multibody System	Danjou et al. (2008)									x			
	He et al. (2012)						x						
Multi-View Product Model	Rasoulifar et al. (2012)	x					x	x					
Node Link Diagram	Bonev et al. (2015)						x	x					
NVH Model	Danjou et al. (2008)									x			
Parametric Associativity Graph	Ameri et al. (2008)						x	x					
Principle Solution Representation Model	He et al. (2013)	x	x				x						

Table 6 (continued)

Product models	References	Included aspects											
		1	2	3	4	5	6	7	8	9	10	11	12
Product Architecture	Feldhusen and Grote (2013)						x	x		x		x	
Product Structure Model	Baxter et al. (2008)						x						x
	Langeveld (2011)		x				x		x	x			
	Wökl and Shea (2009)					x			x				
Prototype	Andreasen et al. (2015)	x											
	Morales et al. (2022)	x					x						
Pseudo Rigid Body Model	Berselli et al. (2016)	x				x	x	x					
	Bilancia et al. (2017)	x					x	x					
Remanufacturability Model	Fang et al. (2014)	x					x	x	x			x	
SAPPhIRE/-lite Model	Sarkar et al. (2017)	x					x	x					
Schematic Representation	Gadeyne et al. (2014)						x	x					
Sketches	Andreasen et al. (2015)	x								x			
	Seybold and Mantwill (2021)	x	x				x						
Solution Chain by Rihtarsic	Rihtaršič et al. (2012)			x	x		x			x			
Statistical Model	Künne and Wieczorek (2010)	x					x	x					
Structure-Behavior-Function Model	Goel et al. (2012)						x	x					
SysML Extension ArchME Model	Chen et al. (2018)	x					x	x					
Symbolic Representations	Andreasen et al. (2015)	x					x	x					
System Graph	Hmina et al. (2021)						x	x	x				
Working Space Model	Beetz et al. (2018)	x			x		x	x					
	Schmitt and Kirchner (2022)	x			x		x						

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Declarations

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