Rethinking how we describe product models in engineering design research

Lukas Paehler[a]*, Patric Grauberger[a] and Sven Matthiesen[a]

[a]*IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*

*Lukas Paehler

IPEK – Institute of Product Engineering

Kaiserstr. 10

76131 Karlsruhe

Germany

E-Mail: lukas.paehler@kit.edu

Preprint – Version: 31 August 2023 – https://doi.org/10.5445/IR/1000164204

Rethinking how we describe product models in engineering design research

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. However, there is no common vocabulary or structure to describe product models in engineering design. This weakens the discourse by preventing a common understanding and fostering ambiguity. To address this problem, this research note formulates three stances on product models that incorporate a vocabulary within a contextual structure as a contribution towards a shared understanding when describing product models and their underlying concepts. These stances are classification-oriented, functionality-oriented, and message-oriented. By discussing the implications of using these stances, it is illustrated how they facilitate comparability, avoid misunderstandings, and reveal links to the state of research.

Keywords: product model, engineering design, design discourse

1. Introduction

Due to their wide range of applications in engineering design, models have earned the reputation of being "The Language of the Designer" (Andreasen 1994, 103). They are used from the beginning of product development up to the manufacturing of the final product for various use cases, such as: (1) representing the design of the product (e.g., Andreasen, Hansen, and Cash 2015; Eckert and Hillerbrand 2018); (2) for collaboration of designers (e.g., A. M. Maier et al. 2014; Eckert and Hillerbrand 2022); and (3) for decision making (e.g., Eckert and Hillerbrand 2022; J. F. Maier, Eckert, and John Clarkson 2017). Hence, models are of great interest to design researchers because of their importance to designers. This is also reflected in the prevalence with which models are described in design research.

A common type of model used in product development, and the focus of this paper, is the product model. These are models that share a limited set of properties with the technical product (Buur and Andreasen 1989), such as the way the components contribute to the main function of the product. Designers are able to interact with the unfinished product through such a product model (Eckert et al. 2015), allowing them, for example, to trace the consequences of a change to a component on the main function. A more detailed introduction to the term *product model* follows in Section 2. While the first product models were 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 based on the changes that affect design practice today. Examples of such changes are (1) the increasing complexity of technical systems (e.g., Suh 2005; Tomiyama et al. 2007); (2) multi-domain teams and products (e.g., Buur and Andreasen 1989); and (3) required modularity (e.g., Baylis, Zhang, and McAdams 2018). Further changes are to 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. Therefore, design research is concerned with a variety of existing and new product models in terms of their present or intended effects on design practice.

The research on product models pursues different objectives. For example, existing approaches to modelling are being further developed in order to open up new application scenarios. This can be seen, for example, in the history of the Design Structure Matrix (hereafter DSM), which originated in engineering management under Steward (1981) and is now available in various types for different areas of application (Eppinger and Browning 2012), and with a large number of extensions (Browning 2016). At the same time, new approaches to building product models are being developed, such as in Wilschut et al. (2018), who automatically build DSMs from textual functional specifications to reduce the effort required. Also, research is carried out on product models without changing them. For example, methods are being developed that integrate an existing product model into a method step using the product model as a tool for making design refinements (e.g., in Alizon, Shooter, and Simpson (2007)). Equally, research into the impact and perception of the use of product models on designers is undertaken (Eisenbart, Gericke, and Blessing 2017). However, these research activities can not be carried out in isolation from each other. For example, new modelling approaches also lead to new applications within methods, and new insights from applications contribute to the refinement of the modelling approaches. This illustrates, due to different starting points and motivations, research on and with product models is carried out with different objectives, which rely on each other's knowledge in the form of the accompanying descriptions of product models.

Looking at the descriptions of product models in the literature, they deviate even in publications that are similar in time, objective, and described product model. This can be demonstrated by two example publications, both of which describe the DSM in the context of its integration into a product family optimisation method: Palani Rajan et al. (2005) and Alizon, Shooter, and Simpson (2007). Palani Rajan et al. (2005) begin with the reason for using the DSM and its value, and then move on to input, modelling steps, and output. Alizon, Shooter, and Simpson (2007), on the other hand, start the description with the represented information, the structure of the representation, and the modelling steps. The structure of the description is thus individual. The descriptions also differ in the vocabulary. While Palani Rajan et al. (2005) describe the intended facilitation for the designer as use, Alizon, Shooter, and Simpson (2007) describe a situation at the beginning of a design process as use. As this example illustrates, there is no common structure or vocabulary to describe product models.

Because of the inconsistent vocabulary, it is difficult to track overarching changes and trends in research on product models as the relationships between the concepts described remain invisible (cf. Cash, Daalhuizen, and Hay 2022). An inconsistent vocabulary also hinders the ability to efficiently communicate research findings to groups outside the research community (Gray 2022) and resembles a lack of consensus to outsiders, which may affect uptake in practice (Gill 1990). This has been noted, e.g., in the context of modularisation (see Bonvoisin et al. 2016) and design methodology (see Hein 1994). Moreover, during development and refinement, researchers must rely on their intuition regarding the concepts of the product models to be considered, which increases the amount of reasoning required (cf. Prochner and Godin 2022). As a consequence, the lack of a common vocabulary hampers researchers' capabilities and the quality of research on product models.

In contrast, as Krippendorff (1995, 139) states, vocabulary "creates a structure within textual matter that is based on selectively (re)cognizing similarities in the compositions or usages of artifacts: (re)combinable and (de)composable forms, components or assemblages, much like words, and syntactic structures." Sharing a common vocabulary in discourse reflects a shared understanding within the domain (Gruber 1993) and counteracts ambiguity (Štorga, Andreasen, and Marjanović 2010), increasing the quality and strength of the discourse (Krippendorff 1995). By discourse, Krippendorff (1995) refers to a particular way of languaging for individuals as well as for groups. Applying the advantages of a common vocabulary to product models, it can be stated that it would improve the quality and strength of the discourse, i.e. (I) make the descriptions of product models easier to compare, (II) avoid misunderstandings, and (III) make changes in the current state of research visible.

So far, there have only been partial approaches to introducing a common vocabulary, such as: (1) classification approaches for product models, (2) frameworks for describing the modelling process (these are thus adjacent in terminology to the finished models), and (3) the breakdown of the understanding of individual terms. As such, Weidmann et al. (2017) have introduced a classification key for product models to compare them with regard to their interdisciplinarity. Buur and Andreasen (1989) developed a categorisation-oriented two-part approach that includes a framework for comparing modelling activities and for considering product models as part of a communication process. Eisenbart, Gericke, and Blessing (2011) build on Buur and Andreasen's (1989) framework by additionally considering the information available in a state for comparing modelling approaches between disciplines. Furthermore, there are contributions, such as J. F. Maier, Eckert, and John Clarkson (2017), which examine a single characteristic of product models in detail and thereby build an understanding of this specific term. Thereby, these approaches provide components of a vocabulary to fulfil specific purposes, but are limited to those purposes and therefore do not provide a coherent vocabulary to describe product models.

In summary, the problem is that there is no common structure or vocabulary in the descriptions of product models, which reduces the quality and strength of the discourse on product models, and previous approaches have not been sufficient to address this situation.

To address this problem, this research note seeks to establish stances towards product models that incorporate a vocabulary within a contextual structure by integrating terms from existing approaches. This contribution is therefore associated with theme 8 of the research notes, “mapping and understanding development in design research” (Cash, Daalhuizen, and Hay 2022), by addressing an issue in terminology and understanding. It also joins and is inspired by the stances on design methods proposed in the research note by Gray (2022). Given the more advanced understanding of the vocabulary used to describe design methods, it is therefore drawn upon.

2. What is a product model in engineering design?

Models represent an original with which they share selected properties, e.g., aesthetics. This original is a phenomenon or object regardless of whether this already exists in the real world. In the required modelling process, through choosing a technique to use and a theory to apply, only a subset of the properties of the original is adopted into the model. Thereby, a simplification of the complexity occurs as not all properties of the original are included. The resulting model can be expressed and communicated by selecting an appropriate representation, e.g., a symbolic representation. Hence, a relationship is created from the modelled phenomenon or object, with the help of a theory and technique in the modelling process, to the model and ultimately to its representation. (Andreasen, Hansen, and Cash 2015)

In the context of this contribution, models in engineering design are considered whose original is a technical product. These models are to be distinguished from process models, such as those described by Eckert and Stacey (2010) or Wynn and Clarkson (2018), which model an existing or a desired design process. In the literature, different notions are used to refer to the models under consideration, such as *product model*, *design model*, and *design representation*, which are also understood in different and overlapping ways. This can be illustrated by the following descriptions of the terms and associated models:

- *Product model* According to Andreasen, Hansen, and Cash (2015, 222), product models are "[...] models that support the progression and final specification of the design via, e.g., technical drawings for manufacturing purpose." Meanwhile, Eckert and Hillerbrand (2018) also include models that arise earlier in a design process, such as analysis and simulation models (which would be design models according to Andreasen, Hansen, and Cash (2015)). Eckert and Hillerbrand (2018) distinguish between generative models, which describe function, behaviour, or structure, and evaluation models, which analyse the behaviour of a design defined by a generative model. Eckert et al. (2015) name sketches, CAD models, and technical drawings as examples. In contrast, (Ehrlenspiel and Meerkamm 2017, 913, translated by the authors) have a more extensive understanding of the term and describe a model that "contains all information relevant to product creation, use and disposal in sufficient completeness".
- *Design model* Andreasen, Hansen, and Cash (2015, 222) describe design models as "[…] intermediate models that support synthesis, communication, and verification activities via, e.g., simulation." These models are refined until their characteristics can be added to the main product model (Andreasen, Hansen, and Cash 2015). According to Eisenbart, Gericke, and Blessing (2011), for example, this term includes concept sketches and technical drawings, while Buur and Andreasen (1989) mention verbal descriptions and functional models.
- *Design representation* Following Eris, Martelaro, and Badke-Schaub (2014), this refers to representations of a design that are created for a purpose with the expectation of delivering a utility when externalised. Representations of

this kind range from sketches to prototypes, according to Pei, I. Campbell, and Evans (2011); Atilola, Tomko, and Linsey (2016) also mention CAD and functional models. Worth mentioning at this point is that Pei, I. Campbell, and Evans (2011) list models as a subcategory of visual design representations which suggests a different conception of the relationship between model and representation compared to the understanding by Andreasen, Hansen, and Cash (2015).

The comparison of the underlying meaning and use of the three terms highlights the commonalities in the intention to support a particular use in favour of the designer and in the constructs they contain. For example, sketches are listed as a contained construct for all three terms. Due to the revealed discrepancies, however, in the context of this contribution, Eckert and Hillerbrand's (2018) understanding of the term product model is resumed. As, on the basis of the understanding of the term, stances are to be derived for the discourse, restriction to intermediate or later models would limit their use in design research. After all, this discourse covers the entire design of a technical product and should not be limited to certain parts of it by the possibility of using different conceptual understandings side-by-side. It can also be seen from the use of the terms that there is no clear separation based on the point in time in a design process as the transition between intermediate and finalizing models is fluid. The use of the term ‘model’ also aims to distinguish it from the representation of a model, as previously described for models in general, following Andreasen, Hansen, and Cash (2015).

Yet Eckert and Hillerbrand (2018) do not provide a coherent definition of the term product model. Therefore, a new definition is necessary for this contribution, which conforms to the understanding according to Eckert and Hillerbrand (2018). This will be derived with the help of the descriptions of the adjacent terms. The baseline is the definition of the term model according to Andreasen, Hansen, and Cash (2015, 42): “A model is a human creation that carries attributes similar to the modelled phenomenon or object.” The “similar attributes” are further elaborated as “models are partial” (Andreasen, Hansen, and Cash 2015, 42). The object or phenomenon is the design of a technical product. For further specification, the fulfilment of a purpose in a certain period of time is required (cf., pragmatism according to Stachowiak (1973, 132)). Based on the time frame for design models and product models described by Andreasen, Hansen, and Cash (2015), the time frame is narrowed down to an engineering design process. Based on the descriptions of generative and evaluative models according to Eckert and Hillerbrand (2018), the purpose is the depiction of function, behaviour, or structure or analysis of the behaviour of a defined design. The combination of these elements results in the following definition: *A product model is a human creation that carries a part of the attributes of a design of a technical product within an engineering design process to depict the function, behaviour, or structure, or for analysing the design.*

A widely used product model is the DSM, or more precisely the Product Architecture Design Structure Matrix (Eppinger and Browning 2012). The DSM is briefly explained here as it will be used as a guiding example in the course of this contribution. It is used as example because the model can be assumed to be widely known with over 1000 publications (Browning 2016) across different domains.

A DSM represents the product architecture by arranging the components of a technical product and their interactions as a square N x N matrix. Due to the clarity of the representation and the possibility of different levels of abstraction, its advantage lies particularly in the development of complex systems. Figure 1 shows two DSMs with different abstraction levels as illustrative examples. The components are labelled with the letters A to C and plotted on rows and columns accordingly. Interactions between the components are shown with X marks. Reading the rows from left to right, one sees, for example, that component B1 has inputs from A1 and B2. A DSM is formed and used by (1) decomposition of a technical product into its components, (2) identification of their relationships, (3) analysis of the components and their relationships, (4) representation, and (5) iterative improvement. (Eppinger and Browning 2012)

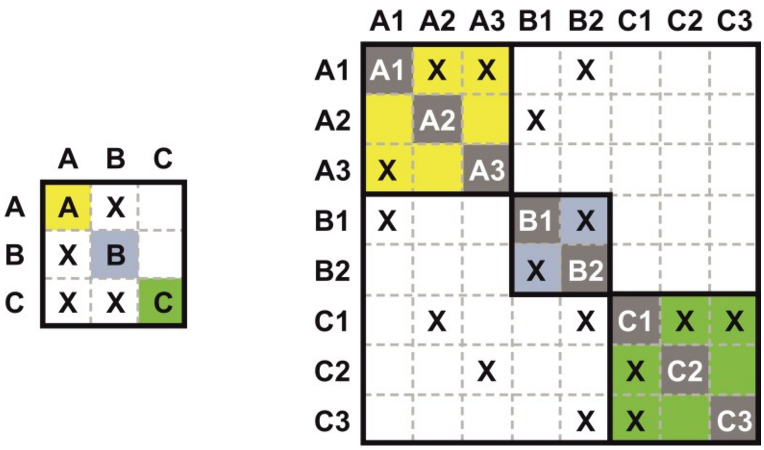

Figure 1. Illustrative example of a DSM at a high (left) and low (right) abstraction level. (Excerpt from Eppinger and Browning (2012, 8))

In conclusion, a product model in engineering design is distinguishable from other models through the modelled object, a technical product, the purpose towards function, behaviour, or structure, and its context within an engineering design process. In this way, the lack of differentiation in the use of the term product model in comparison to the terms *design model* and *design representation* illustrates the lack of a common vocabulary in the discourse as also shown in the introduction, while at the same time establishing the context in which product models are to be considered. The example of the DSM illustrates the characteristics of product models. The modelled object of the DSM is a technical product or parts of one whose product architecture, which belongs to the structure, is carried by the model. Thereby, the DSM depicts the structure but can also be used for analysis, as stated by Eppinger and Browning (2012).

3. Stances towards product models

To enable design researchers to develop, advance, and utilize product models through discourse with others, we formulated three stances towards product models in engineering design. Each stance provides a vocabulary for a set of related concepts. The concepts had not yet been systematically consolidated in the literature, although they reoccurred in varying degrees and forms in design research and practice. Therefore, recurring concepts in the description of product models were associated with existing theory and descriptions until no further concepts were identified. These concepts and their vocabulary determine how researchers think, communicate, and publish their findings, i.e. their understanding. The stances therefore do not represent a new development of concepts, but rather describe a conjunction of understanding of concepts that occur across product models. This conjunction has only considered product models as described in Section 2, however, this should not exclude an application to models outside these boundaries.

To begin with, the resulting stances are outlined briefly as follows. Each of the stances targets typical cases of product model description, spanning the support of model selection and the integration of models into overarching frameworks. Nevertheless, there are similarities and affinities in the underlying concepts of the different stances, and additional stances are also conceivable. Figure 2 provides an overview of the stances and their underlying concepts. The first stance, *classification*, views product models in terms of their contribution to the design of a technical product. This stance provides the information needed to select a product model or to compare multiple models in terms of their intended use. The second stance, *functionality*, views product models as target-oriented tools in a design process at hand to transform an input into an output. As such, this stance looks at the starting and ending points of integrating the product model into a design process and the transformation process that occurs in between. The third stance, *message*, views product models as constructs for sharing knowledge among individuals or systems. In this stance, we look at how product models represent, communicate, and retrieve knowledge.

CLASSIFICATION of product models as to their contribution to a design process	**FUNCTIONALITY** of product models as target-oriented tools in a design process	**MESSAGE** of product models as they are shared among individuals or systems
Collective purpose designer's operation that the model developer intended the product model to address	***Input*** set of descriptive features of a real or artificial product that is chosen and used to build the model	***Medium*** means on which a product model is present and with which it can be handled in space
Individual purpose primary reasons for which designers are to apply the product model in a design process	***Modelling*** sequence of model-creating and model-manipulating actions and steps	***Modelling language*** way in which the knowledge of the model is stored on the medium and provided to a recipient
Attribute characteristics that distinguish a product model in terms of its capabilities in the anticipated use	***Output*** articulation of the product model's information stored during the modelling process	***Captured construct*** data, information, or knowledge that can be retrieved from the model by the recipient
Core idea fundamental working mechanism of the model, and thereby also the basis for understanding the model		

Figure 2. Overview of stances towards product models in engineering design and characterizing concepts (following the visualization of Gray's (2022) stances for design methods)

The following subsections describe the stances and their components in greater depth including their derivation from existing notions in the literature. Each stance is provided with the associated vocabulary and explained in more detail based on its relation to the application in the research. For illustration purposes, the DSM as described in Eppinger and Browning (2012) is used as example through all subsections. Figure 3 provides an overview of how the description of the DSM translates to the stances, which is elaborated within the descriptions of the stances.

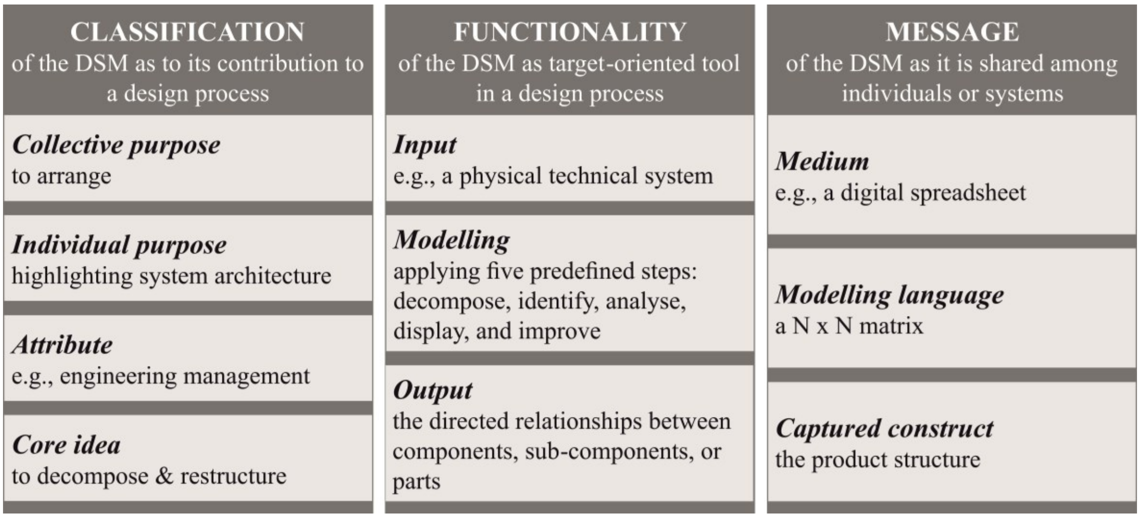

Figure 3. Result of translating the description of the DSM according to Eppinger and Browning (2012) into the structure of the stances.

3.1 Classification-oriented stance

The classification-oriented stance views product models in terms of their contribution to a design process at hand. It combines the *collective and individual purpose* of the model's application, the *attributes* that determine the applicability and potential benefit, and the *core idea*, the working mechanism underlying and specifying the model. Thereby, this stance builds the foundation for contributions structuring the continuously growing state of research of product models (e.g., Weidmann et al. 2017), supporting the selection of models by designers (e.g., Matthiesen et al. 2019), and deriving the lack of product models for new user needs (e.g., Buur and Andreasen 1989; Beetz et al. 2018). However, it does not provide the ability to apply or build a product model only using this information.

The purpose is divided into two complementary components at different levels of abstraction. The ***collective purpose*** is the designer's operation that the model developer intended the product model to address. As Buur and Andreasen (1989, 157) stated, "the purpose is what the designer wants to do with the modelled properties." The operations addressed are shared between various models and can include all basic design operations such as "define, generate (ideas), describe, verify, evaluate, specify, and arrange (information)" (Buur and Andreasen 1989, 157–58). These operations allow a prescription of a product model without taking into account the individuality of the product models. Reflecting on what a designer can do with a DSM, the collective purpose of the DSM, as described by Eppinger and Browning (2012), can be stated as the operation *arrange*. Equally, the collective purpose could be considered to be *describe*, as the DSM provides a description of the product architecture. However, the benefit to the designer is not provided by describing, but by arranging in a formalised way. The use of the basic design operations can be found in other descriptions of product models, such as in Chakrabarti et al. (2011), i.e. *generate*, or as in Muenzer and Shea (2017), i.e. *define*.

The collective purpose is complemented by the ***individual purpose,*** which includes the primary tangible reasons for which designers are to apply a product model in a design process. Tangible in this case relates to an advantage the designer can expect by applying the product model. It is thereby analogue to the purpose of a design method, as described by Gericke, Eckert, and Stacey (2022, 11): "What is the method intended to achieve?" Hence, while the individual purpose provides the tangible reason for the application, the collective purpose enables the arrangement of different models through common design operations. In the example of the DSM as outlined by Eppinger and Browning (2012), the individual purpose is highlighting the technical system's architecture, or in other words, providing a reduced view of relationship patterns between elements. In contrast, other product models offer individual purposes such as a describing the dynamic behaviour of a technical product (Mokhtarian, Coatanéa, and

Paris 2017) or providing the relations between different functions for functional analysis (Ameri et al. 2008).

Attributes are characteristics that distinguish a product model in terms of its capabilities in the anticipated use. They can be characteristics both of the finished model, as well as of the modelling process. In this way, they define criteria to evaluate the suitability of models with regard to a specific situation in a design process, i.e. conditions for the application of a model. Thereby, we follow the understanding of attributes by Gray (Gray, 5), who specify attributes of design methods as “explicit characteristics of the design method that foreground affordance of the method or opportunities to act”. Looking at the DSM as described by Eppinger and Browning (2012), the attributes include the application area, i.e. engineering management, and the depictable information, like components, sub-components, individual parts and their interactions, and matrix display format as representation. In the literature, other known attributes are, for example, the phase of application and discipline as per Weidmann et al. (2017), the type of model as per Eckert and Hillerbrand (2018), required materials as per Gray (2022), and degree of abstraction and modelled properties as per Buur and Andreasen (1989).

The ***core idea*** describes the fundamental working mechanism of the model, and thereby also the basis for understanding the model. It is adopted from Gericke, Eckert, and Stacey (2022, 13), who define the core idea of a design method as “the basic principle, technique or theory that the method employs for generating new information that constitutes the output of the method”. Correspondingly, it can be regarded as an abstract description underlying the modelling technique, which significantly influences the limitations and final structure of the model. In the case of the DSM according to Eppinger and Browning (2012), the core idea has to be derived from the main steps for building the model (see Section 2), i.e. decomposition and restructuring. Accordingly, the core idea of a DSM is to take a technical product apart until an intended level of abstraction is reached, and reunite and interrelate place holders of the elements in a formally defined way. Core ideas can also be found in the form of basic hypotheses (e.g., Grauberger et al. 2020), specific rules (e.g., Bonev et al. 2015), or theoretical assumptions (e.g., Schmitt and Kirchner 2022; Boersting et al. 2008).

3.2 Functionality-oriented stance

From a functionality-oriented stance, product models can be seen as tools that are used in a target-oriented way in a design process at hand. As a tool, what matters is how the product model transforms and refines the description of the product and thereby supports the designer. Consequently, in this stance, the ability of product models to be used to transform an *input* into an intended *output* that is required or helpful for the progress of a design process by *modelling* is considered. Thereby, this stance forms the basis for integrating product models into frameworks and processes, i.e. scheduling the creation and use of the model at a step, (e.g., Nagel et al. 2008), linking product models to accelerate a design process (e.g., Bonev et al. 2015), and understanding the application of the model (e.g., Grauberger et al. 2021).

The ***input*** is the initial set of descriptive features of a real or artificial product that is chosen and used to build the product model. Thereby, our understanding build on the description by Štorga, Andreasen, and Marjanović (2010, 444), who refer to this as "the state of the operand [object of transformations] at the beginning of the transformation process (i.e. material object / design characteristics, etc.)". These features can be virtual, physical, mental, or mixed and can contain data, information, as well as knowledge. For the description of inputs, the description of the required format is also necessary (cf. Section 3.3), so that the modelling process can begin without an additional transformation of the input. In the DSM as described by Eppinger and Browning (2012), the input is a physically available technical system. Equally, a CAD model of the technical system would be possible as input if the level of detail matches the intended level of abstraction of the model. Furthermore, examples of inputs include individual requirements (e.g., Elwert et al. 2019), descriptive equations (e.g., Rihtaršič, Žavbi, and Duhovnik 2012), and prototypes (e.g., Weber 2014).

Modelling refers to the designer's sequence of model creation and manipulation (Roozenburg and Eekels 1995). This is the sum of actions and steps taken by a designer starting from the interaction with the input until the intended, terminated state of the product model is reached. Depending on the modelling procedure used by the designer, a model can serve as input for another iteration of the same model, or be used to form a different model. Eppinger and Browning (2012) describe five modelling steps, starting with the decomposition of the technical system used as input, as described in the introduction of the DSM in Section 2. The decomposition of the system reveals a degree of freedom in this modelling process: The system can be broken down hierarchically into components, sub-components, or individual parts. This has a significant influence on the degree of abstraction of the later product model and its output. For comparison, Eisenbart, Gericke, and Blessing (2017), in turn, describe a multiple step decomposition, starting from the main function of a technical product, through its subfunctions, to the allocation of subsystems that are involved in the fulfilment of the subfunctions.

The ***output*** is the articulation of the product model’s information that was stored during the modelling process in the defined modelling language (cf. Andreasen, Hansen, and Cash 2015, 43). The output can therefore be understood as what is produced towards the purpose and revealed as a result of the completed modelling process (cf. Štorga, Andreasen, and Marjanović 2010). Information gained that does not leave the modelling process, such as findings on not possible realisations in the model, are not part of the output. The output in the case of the DSM is the directed relationships between the elements of the system on the chosen abstraction level resulting from the decomposition of the system (Eppinger and Browning 2012). Likewise, the outputs of product models can be the interrelations that exist between the functions performed in a product (Ameri et al. 2008), or the contribution of subsystems to the functions (Eisenbart, Gericke, and Blessing 2017).

3.3 Message-oriented stance

As product models carry a part of the attributes of a design, they can be used to communicate the constructs formed by this chosen set of attributes. As constructs, we understand the levels in the data-information-knowledge-wisdom hierarchy (DIKW) (e.g., Rowley 2007) provided by the model. Thereby product models become messages exchanged between designers or systems. To reflect this ability, this *message-oriented stance* builds on the view of models as parts of a communication process according to Buur and Andreasen (1989). Buur and Andreasen (1989, 158) describe the process as: "It is a way of transferring information from a sender (the designer) to a receiver (the model user). The information (e.g., ideas, thoughts) is coded by the sender and again decoded by the receiver." For such a use in a communication process, every message requires a *medium* for transmission, a *modelling language* on the medium, and the content recorded with it, the *captured construct*. As such, this stance aids the consideration of models and their abilities as language of designers (see Andreasen 1994) and while in use in knowledge management systems (e.g., D. Tang et al. 2010).

The ***medium*** is the means on which a product model is present and with which it can be handled in space. In a design process, a model can exist as a physical, virtual or mental model, and switch between these spaces (Jones, Snider, and B. Hicks 2020). A product model can not exist without a medium (Buur and Andreasen 1989), and the medium of a product model is specific to the instance of the model being described, but can be changed by a designer as desired. Looking at the example of the DSM as described by Eppinger and Browning (2012), the medium is a digital spreadsheet embedded in a PDF document. Likewise, the DSM could also be available in paper form as an analogue table by printing it out or as a sketched table on a whiteboard. Another example of a medium would be plastic foam used for a physical prototype for simulating the interaction of the user, cardboard, or wood as described by Andreasen, Hansen, and Cash (2015).

The ***modelling language*** is the way in which the knowledge of the product model is stored on the medium and provided to a recipient. Thereby, the modelling language defines the elements and structure of the model, like the language of a letter determines both vocabulary and grammar. Unlike the type of depiction as used by Weidmann et al. (2017) or Matthiesen et al. (2019) or representation, which only specify the type, such as analytical, graphical, textual, the modelling language includes the detailed way of how to store and retrieve the knowledge of the product model. In the case of the DSM according to Eppinger and Browning (2012), the modelling language is the N x N matrix with the conventions for filling the matrix as well as reading it. Alternatively, an equivalent representation as a node link diagram is also possible. Other examples for the modelling language are a particular human language, defined symbols, and drafting standards (Buur and Andreasen 1989).

The ***captured construct*** is the data, information, or knowledge that can be retrieved from the communicated model by the recipient, if the modelling language is understood. Thereby, we follow the understanding of the DIKW hierarchy (see e.g., Rowley 2007), with the product model's capabilities determining the level of the hierarchy that can be achieved. According to B. J. Hicks et al.'s (2002) division of knowledge into knowledge elements and knowledge processes, only knowledge elements can be captured, as knowledge processes exist within a person. Furthermore, wisdom is linked to the way in which knowledge is used and thus strictly linked to the individual user (Rowley 2007). Therefore, the level of wisdom can not be captured by a product model, whereas knowledge can be captured in parts. Following the conception of knowledge by B. J. Hicks et al. (2002), the construct captured in the DSM is the knowledge of the structure of a technical product. This knowledge may vary, as both components, sub-components, or individual parts can be chosen as abstraction level. Furthermore, examples of captured knowledge include the relationships between variables with respect to cause and effect, and the way in which functions are connected (Mokhtarian, Coatanéa, and Paris 2017).

4. From stances towards a refined discourse

The stances are intended to help researchers in their work and communication with each other through a structured vocabulary, thereby influencing the discourse in design research. This section discusses how the proposed stances may affect the discourse in design research. The aim is to strengthen the discourse in the understanding according to Krippendorff (1995) by (I) facilitating comparability, (II) avoiding misunderstandings, and (III) revealing links to the state of research. Since it is not possible to build on a known impact of existing stances, this is done by arguing on the basis of the impact of a common vocabulary and its meaning, and relating it to challenges in product model research.

Comparability relates to recognizable similarities in the used compositions and artifacts as states by Krippendorff (1995). In doing so, the use of the concepts' terminology resembles a composition of interrelated artifacts to enable their direct comparison. In order to ensure that the artefacts are recognisable, they need to be clearly labelled for what they are. For instance, the example of Buur and Andreasen (1989) deriving the need for a new model family can be used for illustration. This model family was supposed to be able to support the development of alternative concepts, and assessment of the consequences of the concepts for development, manufacturing, and marketing early in the concept phase of mechatronic products. The starting point would be the *collective purpose*, in this case both 'generate' and 'evaluate'. Using the concept, corresponding models can be searched for and compared in the state of research, followed by further delimitation via the *individual purpose* and *attribute*. Accordingly, recognizability is also supported by the coherent context in which the concepts are described. If, by contrast, common concepts are not used, it is up to the researchers to understand the descriptions sufficiently to be able to make a thorough comparison without misunderstandings. Comparability of *inputs* and *outputs*, in contrast, related to the effort to identify alternative models for use within a method. Palani Rajan et al. (2005), for example, chose the DSM as it can be built on the basis of interface data, and can derive a tree structure of modules and components from it. If we look at this case on the basis of the *functionality-oriented stance*, the DSM can be replaced by other product models that are built from the same *input* and can deliver the same *output*. Accordingly, the stances, through their concepts, establish a starting point for supporting comparability at the level of abstraction of the concepts themselves.

As shown in the introduction by comparing descriptions by Alizon, Shooter, and Simpson (2007) and Palani Rajan et al. (2005), the meaning behind the vocabulary used in design research diverges, causing ***misunderstandings***. This goes together with diverging meaning used by engineers, where Štorga, Andreasen, and Marjanović (2010,

428) state that “engineers use apparently identical symbols (words, signs, etc.) with different meanings to describe concepts in the PD [product development] domain and utilise these descriptions in different ways.” By bringing the meanings together in the scope of the stances, a reduction of ambiguity takes place. Ambiguity results in an effort to understand the description of another researcher's model, since in this process the meaning of the terms must first be compared. This can be prevented by disclosing the origin of the understanding of the term or by specifying it. If they are not the same, a 'translation' must be carried out between one's own terminology and that of the other researcher. If, instead, the difference is not noticed, a flawed decision can be made in the research based on misunderstood results. Returning to the example of the introduction, Palani Rajan et al. (2005) would call the intended facilitation for the designer a purpose as described in the context of the stances, whereas Alizon, Shooter, and Simpson (2007) would classify the positioning in a design process as an attribute. With this, the stances create the possibility for a reduction of ambiguity and misunderstanding in the context of their structuring levels of abstraction.

The exploitation of ***links to the state of research*** of product models or their components is related to the reuse of knowledge based on a common vocabulary according to Gruber (1993) and is comparable to the identification of relationships between components of methods based on stances, as described by Gray (2022). Both the new development and the advancement of product models start from existing models, which can be considered as a reference in varying degrees. This can range from the use of individual elements of the representation or steps to transform information to the adoption of the basic structure or more. The stances offer a structure here in which existing product models can be described and the product models to be developed can be contrasted against them. At the same time, the use of the stances creates a structure in which product models can be elaborated. The structure thereby specifies what has to be developed, elaborated, or described in order to provide other researchers with a comprehensible overall picture. In this way, it is possible to switch from the classification-oriented stance with a strong reference to the application to the other stances for the content-related development of the product model. The stances thus provide a way of putting the development of one's own product model into a structure that can be continuously and fluently related to other product models.

While the stances facilitate comparability, addressing misunderstanding and links on the level of the concepts, they cannot ensure these objectives in the descriptions below the concepts. Thus, the same core idea can still be described differently by two researchers. While the use of stances allows these core ideas to be contrasted, potentially leading to the recognition of similarity, the vocabulary does not reach levels below the concepts. The scope of influence of the stances as a vocabulary is thus limited to their level of consideration, but structurally they can also have a deeper impact. However, it is therefore still up to each individual researcher to establish the consistency of the vocabulary of the product model description outside of the stances by grounding it in the literature and a possibility to extend the stances in further discussions and research.

5. Conclusion and actionable recommendations

The discourse on product models in design research lacks quality and strength due to the absence of a common vocabulary or comparable structure in the description of product models. To support the discourse among model researchers through a shared understanding, we provided three stances in this research note, each consisting of a set of related concepts shared between product models in engineering design. In doing so, previously unrelated concepts were linked in a coherent structure and given an initial vocabulary. In order for the stances to unfold an impact in design research, they must first find their way into the discourse. We have therefore highlighted opportunities to support the comparability, reduction of misunderstanding, and chance to link with other models resulting from the stances. The opportunities point to the potential for the development of new product models as well as the further development and use of existing product models. When the discussed opportunities are broken down into what each individual researcher can do, four key recommendations for action emerge:

- Before getting started, use the stances to reflect on the structure and concepts of your description that are necessary for another researcher to fully understand your product model description.
- Always describe concepts in their context with related concepts by using the stances' structuring ability to show how they relate to each other so that researchers do not have to waste time searching.
- State the concept of the product model you are describing precisely using the stances' vocabulary so that other researchers can recognise it immediately.
- State the stance or the understanding of the concept on which your description is based, either by references or by a comprehensible derivation.

With the help of these recommendations, an awareness for the use of the vocabulary to describe product models is addressed. The vocabulary thus makes people aware of what is being developed, described and subsequently discussed. Thereby, the stances have a direct influence on the discourse on product models in engineering design. This influence should be used to move towards a more deliberate way of developing and handling product models, taking advantage of synergies between the results of researchers in the community. Hence, it now depends on the continuation of the discussion to improve the discourse on research on product models.

Acknowledgements

The research documented in this manuscript has been funded by the German Research Foundation (DFG) within the project “Research map of models for modelling embodiment and function of technical systems to support linked model usage” (446789859). The support by the German Research Foundation (DFG) is gratefully acknowledged.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alizon, Fabrice, Steven B. Shooter, and Timothy W. Simpson. 2007. “Improving an Existing Product Family Based on Commonality/diversity, Modularity, and Cost.” *Design Studies* 28 (4): 387–409. https://doi.org/10.1016/j.destud.2007.01.002.

Ameri, Farhad, Joshua D. Summers, Gregory M. Mocko, and Matthew Porter. 2008. “Engineering Design Complexity: An Investigation of Methods and Measures.” *Research in Engineering Design* 19:161–79. https://doi.org/10.1007/s00163-008-0053-2.

Andreasen, Mogens Myrup. 1994. “Modelling—The Language of the Designer.” *Journal of Engineering Design* 5 (2): 103–15. https://doi.org/10.1080/09544829408907876.

Andreasen, Mogens Myrup, Claus Thorp Hansen, and Philip Cash. 2015. *Conceptual Design.* Cham: Springer International Publishing.

Atilola, Olufunmilola, Megan Tomko, and Julie S. Linsey. 2016. “The Effects of Representation on Idea Generation and Design Fixation: A Study Comparing Sketches and Function Trees.” *Design Studies* 42:110–36. https://doi.org/10.1016/j.destud.2015.10.005.

Baylis, Kyle, Guanglu Zhang, and Daniel A. McAdams. 2018. “Product Family Platform Selection Using a Pareto Front of Maximum Commonality and Strategic Modularity.” *Research in Engineering Design* 29 (4): 547–63. https://doi.org/10.1007/s00163-018-0288-5.

Beetz, Jean-Paul, Pia Dorothea Schlemmer, Hermann Kloberdanz, and Eckhard Kirchner. 2018. “USING the NEW WORKING SPACE MODEL for the DEVELOPMENT of HYGIENIC PRODUCTS.” In *15th International Design Conference, DESIGN 2018*, 985–96.

Boersting, Peter, R. Keller, Thomas Alink, Claudia Eckert, Albert Albers, and P. John Clarkson. 2008. “The Relationship Between Functions and Requirements for an Improved Detection of Component Linkages.” In *10th International Design Conference, DESIGN 2008*, 309–16.

Bonev, Martin, Lars Hvam, P. John Clarkson, and Anja M. Maier. 2015. “Formal Computer-Aided Product Family Architecture Design for Mass Customization.” *Computers in Industry* 74:58–70. https://doi.org/10.1016/j.compind.2015.07.006.

Bonvoisin, Jérémy, Friedrich Halstenberg, Tom Buchert, and Rainer Stark. 2016. “A Systematic Literature Review on Modular Product Design.” *Journal of Engineering Design* 27 (7): 488–514. https://doi.org/10.1080/09544828.2016.1166482.

Browning, Tyson R. 2016. "Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities." *IEEE Transactions on Engineering Management* 63 (1): 27–52. https://doi.org/10.1109/TEM.2015.2491283.

Buur, Jacob, and Mogens Myrup Andreasen. 1989. "Design Models in Mechatronic Product Development." *Design Studies* 10 (3): 155–62. https://doi.org/10.1016/0142-694X(89)90033-1.

Cash, Philip, Jaap Daalhuizen, and Laura Hay. 2022. "Editorial: Design Research Notes." *Design Studies* 78:101079. https://doi.org/10.1016/j.destud.2021.101079.

Chakrabarti, Amaresh, and Lucienne Blessing, eds. 2014. *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations.* London: Springer London.

Chakrabarti, Amaresh, Kristina Shea, Robert Stone, Jonathan Cagan, Matthew Campbell, Noe Vargas Hernandez, and Kristin L. Wood. 2011. "Computer-Based Design Synthesis Research: An Overview." *Journal of Computing and Information Science in Engineering* 11 (2): 21003. https://doi.org/10.1115/1.3593409.

Eckert, Claudia, Albert Albers, N. Bursac, H. X. Chen, P. John Clarkson, Kilian Gericke, Bartosz Gladysz et al. 2015. "Integrated Product and Process Models: Towards an Integrated Framework and Review." In *Proceedings of the 20th International Conference on Engineering Design, ICED15*, 389–98.

Eckert, Claudia, and Rafaela Hillerbrand. 2018. "Models in Engineering Design: Generative and Epistemic Function of Product Models." In *Advancements in the Philosophy of Design*, edited by Pieter E. Vermaas and Stéphane Vial, 219–42. Design Research Foundations. Cham: Springer International Publishing.

Eckert, Claudia, and Rafaela Hillerbrand. 2022. “Models in Engineering Design as Decision-Making Aids.” *Engineering Studies* 14 (2): 134–57. https://doi.org/10.1080/19378629.2022.2129061.

Eckert, Claudia, and Martin Stacey. 2010. “What Is a Process Model? Reflections on the Epistemology of Design Process Models.” In *Modelling and Management of Engineering Processes*, edited by Peter Heisig, P. J. Clarkson, and Sandor Vajna, 3–14. London: Springer London.

Ehrlenspiel, Klaus, and Harald Meerkamm. 2017. *Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit.* 6., vollständig überarbeitete und erweiterte Auflage. München, Wien: Carl Hanser Verlag GmbH & Co. KG.

Eisenbart, Boris, Kilian Gericke, and Lucienne Blessing. 2011. “A Framework for Comparing Design Modelling Approaches Across Disciplines.” In *Proceedings of the 18th International Conference on Engineering Design, ICED 11*, 344–55.

Eisenbart, Boris, Kilian Gericke, and Lucienne Blessing. 2017. “Taking a Look at the Utilisation of Function Models in Interdisciplinary Design: Insights from Ten Engineering Companies.” *Research in Engineering Design* 28:299–331. https://doi.org/10.1007/s00163-016-0242-3.

Elwert, M., M. Ramsaier, Boris Eisenbart, and R. Stetter. 2019. “Holistic Digital Function Modelling with Graph-Based Design Languages.” *Proceedings of the Design Society: International Conference on Engineering Design* 1 (1): 1523–32. https://doi.org/10.1017/dsi.2019.158.

Eppinger, Steven D., and Tyson R. Browning. 2012. *Design Structure Matrix Methods and Applications.* Engineering systems. Cambridge, Mass, USA: MIT Press.

Eris, Ozgur, Nikolas Martelaro, and Petra Badke-Schaub. 2014. "A Comparative Analysis of Multimodal Communication During Design Sketching in Co-Located and Distributed Environments." *Design Studies* 35 (6): 559–92. https://doi.org/10.1016/j.destud.2014.04.002.

Gericke, Kilian, Claudia Eckert, and Martin Stacey. 2022. "Elements of a Design Method – a Basis for Describing and Evaluating Design Methods." *Design Science* 8. https://doi.org/10.1017/dsj.2022.23.

Gill, H. 1990. "Adoption of Design Science by Industry — Why so Slow?" *Journal of Engineering Design* 1 (3): 289–95. https://doi.org/10.1080/09544829008901659.

Grauberger, Patric, Matthias Eisenmann, J. Stoitzner, and Sven Matthiesen. 2021. "Enhancing Design Method Training with Insights from Educational Research–improving and Evaluating a Training Course for a Qualitative Modelling Method." *SN Applied Sciences* 3 (11). https://doi.org/10.1007/s42452-021-04817-9.

Grauberger, Patric, H. Wessels, Bartosz Gladysz, N. Bursac, Sven Matthiesen, and Albert Albers. 2020. "The Contact and Channel Approach–20 Years of Application Experience in Product Engineering." *Journal of Engineering Design* 31 (5): 241–65. https://doi.org/10.1080/09544828.2019.1699035.

Gray, Colin M. 2022. "Languaging Design Methods." *Design Studies* 78:101076. https://doi.org/10.1016/j.destud.2021.101076.

Gruber, Thomas R. 1993. "A Translation Approach to Portable Ontology Specifications." *Knowledge Acquisition* 5 (2): 199–220. https://doi.org/10.1006/knac.1993.1008.

Hein, Lars. 1994. "Design Methodology in Practice." *Journal of Engineering Design* 5 (2): 145–63. https://doi.org/10.1080/09544829408907880.

Hicks, Ben J., Steve J. Culley, Richard D. Allen, and Glen Mullineux. 2002. "A Framework for the Requirements of Capturing, Storing and Reusing Information and Knowledge in Engineering Design." *International Journal of Information Management* 22 (4): 263–80. https://doi.org/10.1016/S0268-4012(02)00012-9.

Jones, D. E., C. Snider, and B. Hicks. 2020. "A FRAMING of DESIGN as PATHWAYS BETWEEN PHYSICAL, VIRTUAL and COGNITIVE MODELS." *Proceedings of the Design Society: DESIGN Conference* 1:41–50. https://doi.org/10.1017/dsd.2020.128.

Krippendorff, Klaus. 1995. "Redesigning Design; an Invitation to a Responsible Future." In *Design: Pleasure or Responsibility*, edited by P. Tahkokallio and S. Vihma, 138–62: Helsinki: University of Art and Design. https://repository.upenn.edu/asc_papers/46/.

Maier, Anja M., David Wynn, Thomas J. Howard, and Mogens Myrup Andreasen. 2014. "Perceiving Design as Modelling: A Cybernetic Systems Perspective." In Chakrabarti and Blessing 2014, 133–49.

Maier, J. F., Claudia Eckert, and P. John Clarkson. 2017. "Model Granularity in Engineering Design – Concepts and Framework." *Design Science* 3 (E1). https://doi.org/10.1017/dsj.2016.16.

Matthiesen, Sven, Patric Grauberger, Frank Bremer, and K. Nowoseltschenko. 2019. "Product Models in Embodiment Design: An Investigation of Challenges and Opportunities." *SN Applied Sciences* 1 (9). https://doi.org/10.1007/s42452-019-1115-y.

Mokhtarian, Hossein, Eric Coatanéa, and Henri Paris. 2017. "Function Modeling Combined with Physics-Based Reasoning for Assessing Design Options and

Supporting Innovative Ideation." *AIEDAM* 31 (04): 476–500. https://doi.org/10.1017/S0890060417000403.

Muenzer, Clemens, and Kristina Shea. 2017. "Simulation-Based Computational Design Synthesis Using Automated Generation of Simulation Models from Concept Model Graphs." *Journal of Mechanical Design* 139 (7): 71101. https://doi.org/10.1115/1.4036567.

Nagel, Robert L., Robert Stone, Ryan S. Hutcheson, Daniel A. McAdams, and Joseph A. Donndelinger. 2008. "Function Design Framework (FDF): Integrated Process and Function Modeling for Complex Systems." In *Proceedings of the ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 4: 20th International Conference on Design Theory and Methodology; Second International Conference on Micro- and Nanosystems*, 273–86: ASME.

Palani Rajan, P. K., Michael van Wie, Matthew Campbell, Kristin L. Wood, and Kevin N. Otto. 2005. "An Empirical Foundation for Product Flexibility." *Design Studies* 26 (4): 405–38. https://doi.org/10.1016/j.destud.2004.09.007.

Pei, Eujin, Ian Campbell, and Mark Evans. 2011. "A Taxonomic Classification of Visual Design Representations Used by Industrial Designers and Engineering Designers." *The Design Journal* 14 (1): 64–91. https://doi.org/10.2752/175630610X12877385838803.

Prochner, Isabel, and Danny Godin. 2022. "Quality in Research Through Design Projects: Recommendations for Evaluation and Enhancement." *Design Studies* 78:101061. https://doi.org/10.1016/j.destud.2021.101061.

Rihtaršič, Janez, Roman Žavbi, and Jože Duhovnik. 2012. “Application of Wirk Elements for the Synthesis of Alternative Conceptual Solutions.” *Research in Engineering Design* 23:219–34. https://doi.org/10.1007/s00163-012-0127-z.

Roozenburg, Norbert F. M., and Johannes Eekels. 1995. “Product Design: Fundamentals and Methods.”.

Rowley, Jennifer. 2007. “The Wisdom Hierarchy: Representations of the DIKW Hierarchy.” *Journal of Information Science* 33 (2): 163–80. https://doi.org/10.1177/0165551506070706.

Schmitt, Florian, and Eckhard Kirchner. 2022. “The Quantitative Working Space Model.” In *DS 118: Proceedings of Nord Design 2022*, 1–12.

Stachowiak, Herbert. 1973. *Allgemeine Modelltheorie.* Wien: Springer Verlag.

Steward, Donald V. 1981. “The Design Structure System: A Method for Managing the Design of Complex Systems.” *IEEE Transactions on Engineering Management* EM-28 (3): 71–74. https://doi.org/10.1109/TEM.1981.6448589.

Štorga, Mario, Mogens Myrup Andreasen, and Dorian Marjanović. 2010. “The Design Ontology: Foundation for the Design Knowledge Exchange and Management.” *Journal of Engineering Design* 21 (4): 427–54. https://doi.org/10.1080/09544820802322557.

Suh, Nam P. 2005. “Complexity in Engineering.” *CIRP Annals* 54 (2): 46–63. https://doi.org/10.1016/S0007-8506(07)60019-5.

Tang, Dunbing, Renmiao Zhu, Jicheng Tang, Ronghua Xu, and Rui He. 2010. “Product Design Knowledge Management Based on Design Structure Matrix.” *Advanced Engineering Informatics* 24 (2): 159–66. https://doi.org/10.1016/j.aei.2009.08.005.

Tomiyama, T., V. D'Amelio, J. Urbanic, and W. ElMaraghy. 2007. "Complexity of Multi-Disciplinary Design." *CIRP Annals* 56 (1): 185–88. https://doi.org/10.1016/j.cirp.2007.05.044.

Weber, Christian. 2014. "Modelling Products and Product Development Based on Characteristics and Properties." In Chakrabarti and Blessing 2014, 327–52.

Weidmann, Dominik, Moritz Isemann, Peter Kandlbinder, Christoph Hollauer, Niklas Kattner, Lucia Becerril, and Udo Lindemann. 2017. "Product Models in Mechatronic Design: Literature Analysis on the Interdisciplinary Character of Product Models." In *2017 Portland International Conference on Management of Engineering and Technology (PICMET)*, 1–7: IEEE.

Wilschut, T., L. F.P. Etman, J. E. Rooda, and J. A. Vogel. 2018. "Generation of a Function-Component-Parameter Multi-Domain Matrix from Structured Textual Function Specifications." *Research in Engineering Design* 29:531–46. https://doi.org/10.1007/s00163-018-0284-9.

Wynn, David, and P. John Clarkson. 2018. "Process Models in Design and Development." *Research in Engineering Design* 29:161–202. https://doi.org/10.1007/s00163-017-0262-7.