**NORDDESIGN CONFERENCE**
REYKJAVIK, ICELAND, 12-14 AUGUST 2024

# A Framework for Integrating and Utilizing Knowledge on Product Models for Engineering Design Research

Lukas Paehler, Patric Grauberger, Sven Matthiesen

Karlsruhe Institute of Technology (KIT), IPEK – Institute of Product Engineering, Germany

**Abstract:** Research on product models is essential for providing engineering designers with appropriate models. However, this research is difficult as many different product models are used in engineering design, and the knowledge about them is scattered in many different publications. Therefore, in this paper, we present the conceptualization of a framework for knowledge on product models, building on a previous literature review. This framework aims to integrate multiple subfields of knowledge into a landscape of product models so that it can be accessed and utilized more efficiently by researchers.

*Keywords: Design Models, Model-Based Engineering, Design Research*

## 1 Introduction

### 1.1 Motivation

Product models are essential tools in engineering design processes for defining, describing, visualizing, and investigating the product being designed (e.g., Buur and Andreasen, 1989; Maier et al., 2014). A product model in engineering design is characterized as *"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, p. 1), based on the definitions by Andreasen et al. (2015), Stachowiak (1973), and Eckert and Hillerbrand (2018). Examples of such product models are the Function Structure (e.g., Pahl et al., 1996), Contact & Channel Model (e.g., Matthiesen et al., 2018), and Design Structure Matrix (e.g., Browning, 2001). During design processes, designers select the most appropriate product model for a specific situation and therefore have to switch between different models (Jones et al., 2020). Thereby, they create a sequence of product models of different aspects of the product to answer questions, e.g., regarding the functionality or manufacturability, of the unfinished product (Andreasen, 1994). To support them in modeling the different aspects, model researchers continuously develop and advance product models according to the current and upcoming needs of designers.

An ever-increasing amount of knowledge is generated by the researchers who develop and advance product models, as can be seen from the example of the extensions and innovations of the Design Structure Matrix summarized by Browning (2016). Such knowledge includes, for example, insights from specific use cases (e.g., Wettstein et al., 2021), new modeling approaches (e.g., Wilschut et al., 2018), the integration of models into design methods (e.g., Palani Rajan et al., 2005), the combination of models into new models or frameworks (e.g., He et al., 2013), and the classification of multiple models (e.g., Weidmann et al., 2017). These subfields, from which new knowledge about product models emerges, illustrate the need for researchers to consider the changing research environment around them, as the research cannot be done in isolation. For example, new modeling approaches lead to new possibilities for the integration of models into design methods, and new insights from applications contribute to the refinement of modeling approaches, requiring that this research may not be isolated (cf. Paehler et al., 2023). Researchers are therefore dependent on being able to recognize, contextualize, and understand the knowledge relevant to their research activity, regardless of whether it is research on the same, a similar, or a different product model or research objective.

And yet, in the current state of research, it is complicated to access this knowledge. Different researchers can describe the same product models by using different vocabulary, as can be seen for example in the descriptions of the Design Structure Matrix of Alizon et al. (2007) and Palani Rajan et al. (2005). Such inconsistent vocabulary makes it hard to track overarching changes, trends, and relationships (Cash et al., 2022) and hinders the ability to efficiently share research findings (Gray, 2022). Further, links and similarities between different product models are only shown for selected facets and only in hindsight. For example, Weidmann et al. (2017) categorized product models according to their type of depiction, type of information, discipline, and engineering phase. Thus, the comparability established based on the similarities is limited to the categories and product models included at that time. Another example is the structured depiction of links between product models by Paehler and Matthiesen (2024), in which product models were linked to each other based on matches between their outputs and inputs. In this structured depiction, other concepts, such as the purpose of the modeling activity as stated by Andreasen (1994), were disregarded, which means that this additional information would have to be added laboriously to derive a purposeful combination of models. As these examples show, the knowledge on product models is scattered over many different publications and must be compiled for its utilization in research. Hence, the problem is that there is no overarching structure for product model knowledge, e.g., links and similarities between different models, resulting in difficulties in utilizing knowledge between product model researchers.

### 1.2 Research focus

Utilizing knowledge efficiently is a foundation for further progress in product model research. The aim of this paper is therefore to conceptualize a framework for collective knowledge on product models. This framework is intended to provide an overarching structure for knowledge on product models, integrating the various subfields of knowledge and relating them to each other for use by model researchers. It seeks to make similar product models recognizable so that researchers can more easily access product models and their shared knowledge outside of their acquaintance to learn from and build on other models. Thus, the framework is intended to be a tool to facilitate and accelerate future research, for example, research on model selection or modeling theory. Furthermore, unlike a literature review, the framework is not meant to be static, but rather oriented toward the integration of future research findings.

As a starting point for the framework of knowledge on product models, the visualization of the recent literature review by Paehler and Matthiesen (2024) is used. The visualization called “landscape of product models in embodiment design” is focused on the links between product models, i.e., the possibilities to use the outputs of one model as inputs for a subsequent model, and is described in Section 2. As it is focused on relating product models to each other, it is suitable as a starting point and to be advanced through including further subfields of knowledge, which are described in Section 3. The integration is described in Section 4 and its implications are discussed in Section 5.

## 2 The landscape of product models

Figure 1 shows the current landscape of product models which was derived from a systematic literature review on product models in embodiment design as part of engineering design by Paehler and Matthiesen (2024). The product models identified in embodiment design (depicted as black circles) were analyzed and the descriptions of their inputs and outputs were extracted. These descriptions were subsequently analyzed to build categories of common inputs or outputs (depicted as green squares). Matching inputs and outputs of models or categories were considered a link and established between all product models and categories (depicted as directed edges). Subsequently, the layout of the landscape was calculated using the force-directed Yifan Hu layout algorithm (see Hu, 2005) with the network visualization software Gephi (see Bastian et al., 2009). Hence, the landscape is a visualization of the state of research of product models in embodiment design structured by their links to each other, with linked product models positioned closer together and unlinked product models positioned further apart. (Paehler and Matthiesen, 2024)

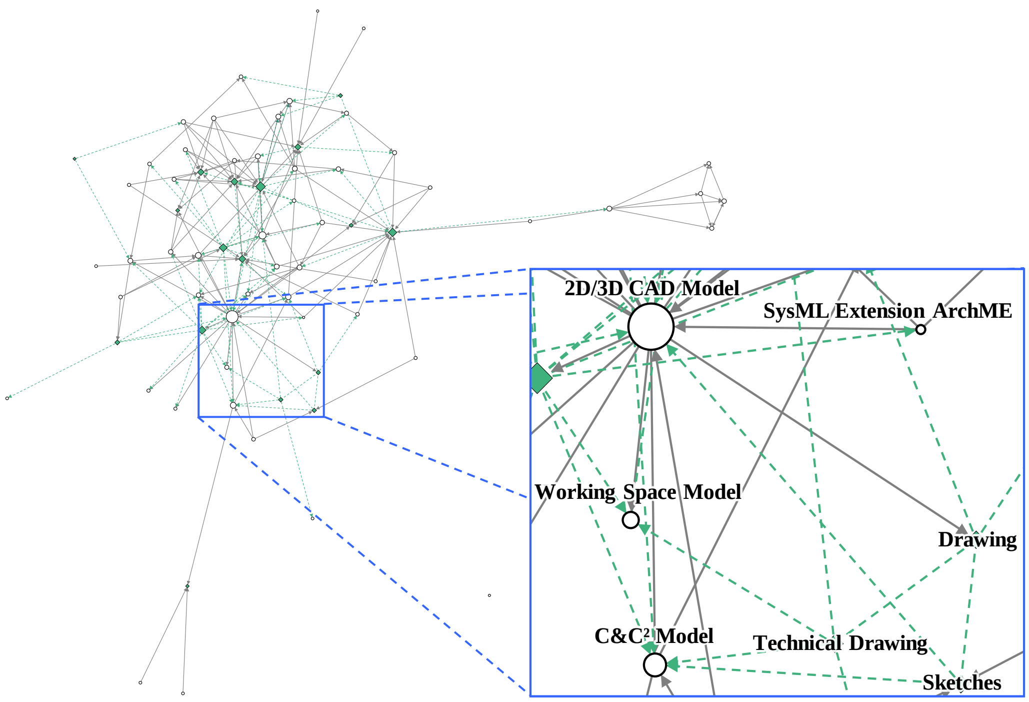


Figure 1. Landscape of product models in embodiment design with an enlarged section (product models = empty black circles; categories of inputs and outputs = filled green squares; links starting at product models = solid gray edges; links starting at categories = dashed green edges) (created from the data of Paehler and Matthiesen (2024))

## 3 Knowledge on product models outside the landscape

This section looks into knowledge on product models outside the landscape from Section 2 and provides examples of what this knowledge is utilized for. To structure the variety of publications on knowledge and their described utilizations, these were grouped into three categories (cf. Paehler et al., 2023): classification-, functionality-, and message-oriented knowledge. This grouping into subfields of knowledge was based on similarities in the knowledge utilized.

### 3.1 Classification-oriented knowledge

Classification-oriented knowledge focuses on distinguishing features of product models. In the following, we describe how this knowledge enables researchers to assess multiple product models against each other, identify missing product models, and provides the basis for selecting a model or comparing it concerning the intended purpose:

- Eisenbart et al. (2011) and Weidmann et al. (2017) used categories to create comparability for the assessment of several product models. Eisenbart et al. (2011) applied generic design states, e.g., the product proposal or principle solution, which reflect similar information on a similar level of detail and abstraction. Thereby, product models can be compared in terms of their way of modeling their included information. In contrast, Weidmann et al. (2017) used categories, e.g., the type of depiction and type of information, to investigate the interdisciplinary character of product models in mechatronic design.

- Buur and Andreasen (1989) introduced a morphology of characteristics related to product models and thereby defined important terms. The morphology was structured into the modeling activity and model itself, thereby structuring the characteristics such as ‘purpose’ or ‘user’. It was subsequently used to derive the need for a new family of concept models intended for the early phases of mechatronic design.

- Matthiesen et al. (2019) and Kohn et al. (2012) aimed to improve the application of product models by supporting the selection. For this reason, Matthiesen et al. (2019) adopted categories from Weidmann et al. (2017) and supplemented them to develop a product model framework as part of a guideline for model selection. Kohn et al. (2012), in contrast, used the content of product models, the application phase in the development process, and the information representation for classification, considering the classification as a step towards a methodology to enable designers to choose product models.

In conclusion, researchers use different types of classifications to structure the state of research in terms of the distinguishing features of product models according to their needs in a specific use case.

### 3.2 Functionality-oriented knowledge

Functionality-oriented knowledge focuses on the inputs, internal mechanisms, and outputs of product models. The following describes how this knowledge enables researchers to integrate models into a design process through, e.g., design methods, enables researchers to combine different product models, and to investigate the work with one or more product models:

- Alizon et al. (2007) and Bonev et al. (2015) used product models as parts of design methods. To do this, they focused on what information they required to build the models and what they could thereby do with the models. In the methods, the models were used for individual or multiple steps and the modeling is linked to the preceding and subsequent method steps or another model. The models therefore served as tools to enable the flow of information through the methods.

- Grauberger et al. (2020a) and Nagel et al. (2008), in contrast, combined separate product models into coherent approaches. They used both their knowledge of the possible inputs and outputs of the models as well as common nomenclatures to create links between the models. The resulting approaches served to make the advantages of the otherwise separate models readily available to designers at the same time.

- Wettstein et al. (2021) and Eisenbart et al. (2017) gathered knowledge about the weaknesses and potential of product models through their use. As such, Wettstein et al. (2021) applied a sequence of product models in a case study and, among other things, identified a weakness of the investigated product model resulting from the requirements of the use case concerning modeling dynamic changes of the system. Eisenbart et al. (2017), meanwhile, investigated applications of a specific group of models in the industry to identify future potential and the need for support by gaining insights into the work of designers with the models.

In summary, the interaction of product models within themselves and with the surrounding design process, e.g., methods, models, and designers is used to investigate the possibilities of linking a model and the associated weaknesses, e.g., applicability or usefulness.

### 3.3 Message-oriented knowledge

Message-oriented knowledge focuses on product models as carriers of information that can be exchanged between people and systems. The following describes how this allows researchers to describe design as a communication process, to consider the switches between product models, and to investigate their use in knowledge management:

- Buur and Andreasen (1989) and Maier et al. (2014) elaborated on the view of product models as part of a communication process in which the model transmits information from a sender to a receiver. In this process, the model had to be available as a particular 'code' to be understood by the sender and receiver and had to exist on a 'medium', such as handwriting on a piece of paper. Maier et al. (2014), thereby, outlined the considerations involved in creating a model to communicate content appropriately.

- Jones et al. (2020) used the ‘medium’ to characterize the groups of physical, virtual, and cognitive models. Based on this characterization, they outlined a framework of design in terms of these groups and the switches that occur between them, e.g., to focus on improving the switches for an accelerated design process.

- In contrast to the previous theoretical considerations, Tang et al. (2010) developed a product design knowledge management around the Design Structure Matrix. It is used to capture and manage design knowledge to improve the understanding of design routes and history by relating designed items to e.g., rationales. Thereby, the capabilities of the Design Structure Matrix for managing design knowledge were illustrated.

Consequently, for the applications described, researchers need to know what information can be managed by a product model, what mediums are possible, and what code is used and therefore needs to be understood.

## 4 A framework for knowledge on product models for engineering design research

The subfields of knowledge from Section 3 were subsequently integrated into the landscape of product models to achieve a coherent framework of knowledge on product models for engineering design research. For each subfield, we describe how the respective knowledge was integrated into the framework. To illustrate the content of the framework, its content is shown in Figures 2 to 4 for two exemplary product models, the Working Space Model (see Beetz et al., 2018) and the Contact and Channel Model (see Grauberger et al., 2020b). Furthermore, it was taken into account that it is planned to digitize the framework for future use and refinement by researchers, so the possibility of software integration of the framework was considered.

### 4.1 Integrating classification-oriented knowledge

The landscape as described in Section 2 already contained categories of common inputs and outputs which are comparable to a classification. These were represented as green squares (see Figure 1). However, this representation was based on the categories themselves being inputs and outputs. As this is not necessarily the case for the classifications introduced in Section 3, this depiction of categories was not adopted into the framework. Instead, the classifications were integrated using a colored flag system. Figure 2 shows the implementation of this colored flag system. Each variant of a category is represented by an individually colored flag, which is depicted in the landscape above the respective product model and thereby enables the depiction of several categories for each product model simultaneously.

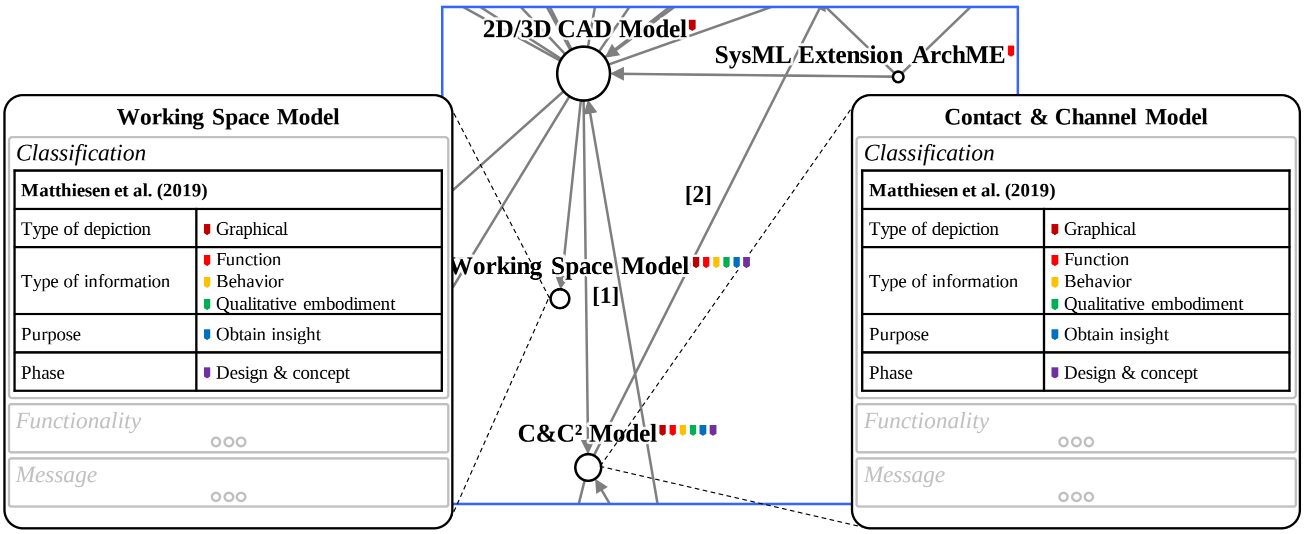


Figure 2. Representation of classification-oriented knowledge within the framework

In the examples of the Working Space Model and Contact & Channel Model, Figure 2 shows their classification according to Matthiesen et al. (2019). The two product models are classified identically, as they are assigned to the same type of depiction, type of information, purpose, and phase, as shown by their identically colored flags. In contrast, the colored flags show that the 2D/3D CAD Model matches the type of depiction of the two example models, but its remaining classification is different.

### 4.2 Integrating functionality-oriented knowledge

The functionality relies on the mechanisms of action into, within, and out of product models that occur when the model is built or used. Some of the therefore relevant inputs and outputs were already present in the landscape if a matching input existed for the output in question. To integrate further linking options, also involving inputs and outputs without match and modeling, a representation as block diagrams was integrated. The block diagram shows the modeling steps, how they interact within the boundaries of the model, and the inputs and outputs that cross the model boundaries. Further, this simplified representation can be used to pinpoint weaknesses identified in case studies or other applications. The implementation of the representation in the landscape is shown in Figure 3.

For example, for the Working Space Model as described by Beetz et al. (2018), a visualization of a technical system can be used to build up the model, resulting in the working space topology of the system. For comparison, the Contact & Channel Model as described by Matthiesen et al. (2018) can also be built from a visualization of a technical system but provides the embodiment function relations of the system and distinguishes two ways of modeling depending on the use case. The similarity of these model's inputs is also represented in the landscape itself, with both of them linked to the 2D/3D CAD Model.

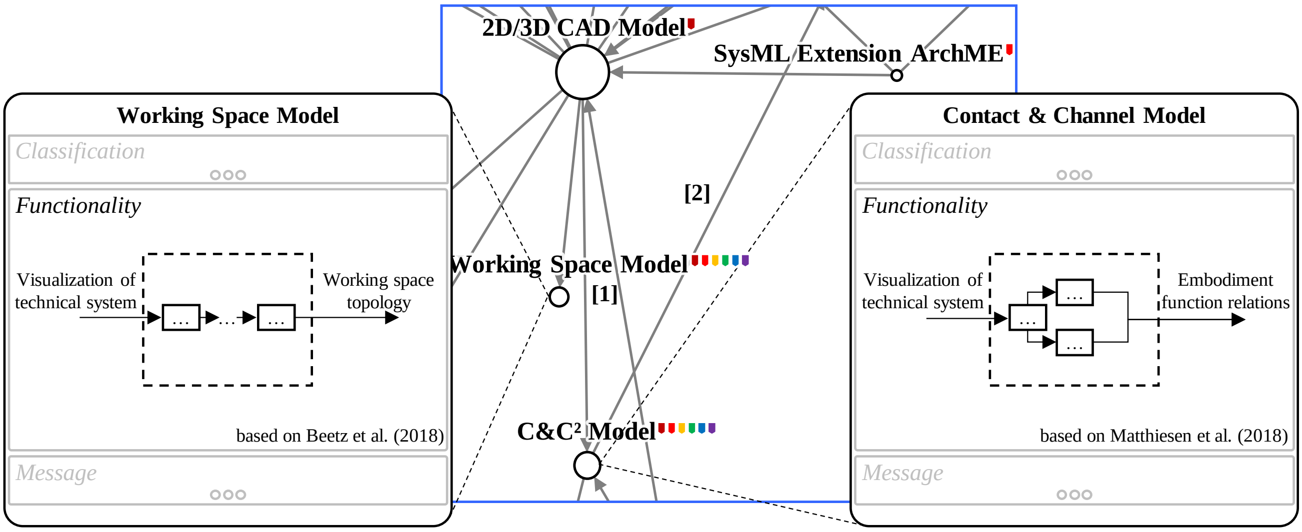


Figure 3. Representation of functionality-oriented knowledge within the framework

### 4.3 Integrating message-oriented knowledge

The knowledge associated with product models as messages was integrated into the framework using the models themselves. This is done by annotating the respective model with the information it represents and the code used for the representation. This creates a direct association between the carried information and the code, i.e., modeling language applied. Since the information may vary depending on the application, the annotation is application-specific and supported by a reference. In addition, the medium used in the application is indicated. Figure 4 shows the implementation into the framework.

In the example of the Working Space Model according to Beetz et al. (2018), the implementation of the model in the framework shows an abstract representation of the technical system with predefined elements. The elements are similar to a block diagram due to the blocks and connections between them. The blocks represent 'working spaces' that are connected by material/food flows. Furthermore, unwanted connections are depicted in red. The Contact & Channel Model according to Grauberger et al. (2020b) also shows predefined elements, but positioned on a technical drawing. The connection to the environment is represented by a 'connector' element, which is followed by a sequence of 'channel and support structures' and 'working surface pairs' representing the flow of forces within components and contact surfaces between these components. Both example models were provided in a PDF file.

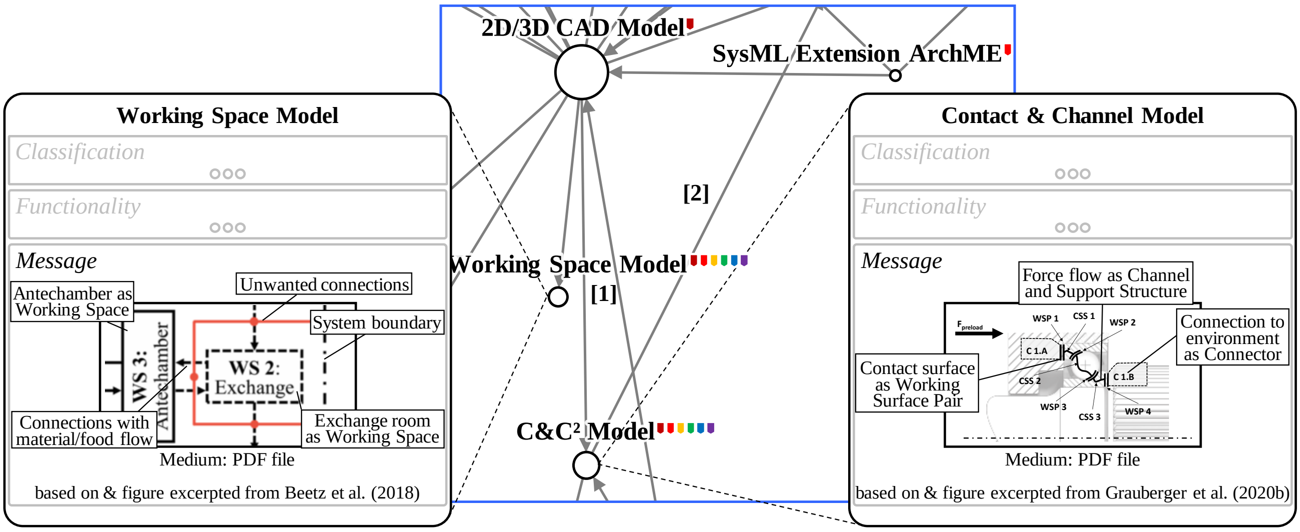


Figure 4. Representation of message-oriented knowledge within the framework

## 5 Discussion

The presented framework provides an overarching structure that allows existing research results on product models, such as classifications or use cases, to be brought together and related to each other. Although the knowledge about product models is still distributed across different publications, the structure of the framework and the referencing of the publications facilitates their access, and key findings, such as the carried information, are shared in comparable representations within the framework. This reduces the otherwise time-consuming search for knowledge relevant to a product model in engineering design. In addition, findings that are supported by a large number of publications and are therefore considered reliable can be identified and further research on these aspects can be avoided, while conflicting findings that indicate the need for further research can be revealed. However, this does not replace the insights provided by reading and analyzing a publication on a product model in detail. Further, vocabulary that differs between publications is not eliminated, as the framework does not define a specific vocabulary. Nevertheless, the framework can be used to identify publications independently of the vocabulary and to compare them regardless of the used vocabulary concerning the knowledge included in the framework.

For example, if the objective would be to integrate a product model into a design method for the design of hydraulic technical systems, e.g., pumps, the framework could be used to evaluate the suitability of product models. In the case of the example models Working Space Model and Contact & Channel Model, the implementation of these models in the framework shows that they do not differ in terms of their classification (see Figure 2) and their input (see Figure 3). Looking at the output and the information it contains (see Figure 4), researchers can determine that the Working Space Model can represent throughflow spaces, which is not known for the Contact & Channel Model. Therefore, in this example scenario, utilizing the framework would assist researchers in selecting an appropriate product model for the design method. Example scenarios of this kind could also be used to evaluate the framework in the future. With this aim in mind, the framework could initially be implemented in analog as a minimal example for a limited number of product models in order to enable early application and evaluation by researchers. This would allow researchers to apply the framework to their own research projects in a workshop, identifying the strengths and weaknesses of the framework and laying the basis for its acceptance.

To support researchers in experiencing the benefits described, the framework could also be implemented in open software and the existing knowledge on product models should be added. This software implementation would also support the evaluation of the framework in usage. As such, the extent to which researchers benefit from the framework in terms of utilizing and sharing knowledge cannot be answered conclusively at this conceptual stage. Furthermore, a technical implementation would allow for the collection of feedback based on the application to further develop the framework. This feedback would make it possible to identify further needs of researchers. Implementation in an open source project would offer the advantage that researchers not only utilize the framework but can also make a direct contribution to its further development and incorporate their own preferences into its composition. Similar to product models themselves, the framework could thereby evolve and adapt to its users.

Moreover, based on the conceptual state of the framework, no statement can be made about its completeness. So far, the landscape and subfields of knowledge on product models listed in Section 3 have been integrated into the framework. This was done aiming to ensure a broad knowledge base that addresses a wide range of applications by researchers.

Nevertheless, it cannot be ruled out that a subfield is missing, but this does not refute the conceptualization. Missing aspects or other subfields of knowledge can be identified through application by researchers after software implementation or also by discussion of the framework in the community. This has the advantage that the framework can be optimized before a time-consuming technical implementation takes place. Supplementing other fields of knowledge or including the large number of publications that exist for some product models in the future, however, bears the risk of reducing the desired level of overview within the framework. In this respect, a balance must be reached between completeness and usefulness of knowledge for researchers.

## 6 Conclusion

The utilization of knowledge on product models among researchers in engineering design research is complicated by the fact that it is scattered among many publications without an overarching structure, concealing links and similarities between different models. To address this problem, this paper presents a framework for knowledge on product models for engineering design research. This framework integrates the subfields of classification-, functionality-, and message-oriented knowledge into an interlinked landscape of product models. The knowledge and publications are thereby merged and related to each other to make it easier for researchers to access and utilize the knowledge gained and provided by others. Thereby, the framework is a support for researchers to benefit from the results on multiple product models within the research community which might otherwise have remained unnoticed. However, as this framework is conceptual, further work and discussion are needed to evaluate its usability and completeness for use by researchers in their daily work.

## Acknowledgments

The research described 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.

## References

Alizon, F., Shooter, S.B., Simpson, T.W., 2007. Improving an existing product family based on commonality/diversity, modularity, and cost. Design Studies 28, 387–409. https://doi.org/10.1016/j.destud.2007.01.002.

Andreasen, M.M., 1994. Modelling—The Language of the Designer. Journal of Engineering Design 5, 103–115. https://doi.org/10.1080/09544829408907876.

Andreasen, M.M., Hansen, C.T., Cash, P., 2015. Conceptual Design. Springer International Publishing, Cham.

Bastian, M., Heymann, S., Jacomy, M., 2009. Gephi: An Open Source Software for Exploring and Manipulating Networks. ICWSM 3, 361–362. https://doi.org/10.1609/icwsm.v3i1.13937.

Beetz, J.-P., Schlemmer, P.D., Kloberdanz, H., Kirchner, E., 2018. Using the new working space model for the development of hygienic products, in: 15th International Design Conference, DESIGN 2018, Dubrovnik, Croatia. 21.-24 May, pp. 985–996.

Bonev, M., Hvam, L., Clarkson, P.J., Maier, A.M., 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.

Browning, T.R., 2001. Applying the design structure matrix to system decomposition and integration problems: a review and new directions. IEEE Transactions on Engineering Management 48, 292–306. https://doi.org/10.1109/17.946528.

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

Buur, J., Andreasen, M.M., 1989. Design models in mechatronic product development. Design Studies 10, 155–162. https://doi.org/10.1016/0142-694X(89)90033-1.

Cash, P., Daalhuizen, J., Hay, L., 2022. Editorial: Design Research Notes. Design Studies 78, 101079. https://doi.org/10.1016/j.destud.2021.101079.

Eckert, C., Hillerbrand, R., 2018. Models in Engineering Design: Generative and Epistemic Function of Product Models, in: Vermaas, P.E., Vial, S. (Eds.), Advancements in the Philosophy of Design. Springer International Publishing, Cham, pp. 219–242.

Eisenbart, B., Gericke, K., Blessing, L., 2011. A framework for comparing design modelling approaches across disciplines, in: DS 68-2: Proceedings of the 18th International Conference on Engineering Design (ICED 11): Impacting Society through Engineering Design, Vol. 2: Design Theory and Research Methodology. ICED, Lyngby/Copenhagen, Denmark. 15.-19.08.2011, pp. 344–355.

Eisenbart, B., Gericke, K., Blessing, L., 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.

Grauberger, P., Goetz, S., Schleich, B., Gwosch, T., Matthiesen, S., Wartzack, S., 2020a. A conceptual model combination for the unification of design and tolerancing in robust design. Proc. Des. Soc.: Des. Conf. 1, 157–166. https://doi.org/10.1017/dsd.2020.12.

Grauberger, P., Wessels, H., Gladysz, B., Bursac, N., Matthiesen, S., Albers, A., 2020b. The contact and channel approach–20 years of application experience in product engineering. Journal of Engineering Design 31, 241–265. https://doi.org/10.1080/09544828.2019.1699035.

Gray, C.M., 2022. Languaging design methods. Design Studies 78, 101076. https://doi.org/10.1016/j.destud.2021.101076.

He, B., Song, W., Wang, Y., 2013. A feature-based approach towards an integrated product model in intelligent design. Int J Adv Manuf Technol 69, 15–30. https://doi.org/10.1007/s00170-013-4991-0.

Hu, Y., 2005. Efficient, high-quality force-directed graph drawing. Mathematica journal 10, 37–71.
Jones, D.E., Snider, C., Hicks, B., 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.
Kohn, A., Lutter-Günther, M., Hagg, M., Maurer, M. (Eds.), 2012. Handling Product Information-Towards an Improved Use of Product Models in Engineering Design.
Maier, A.M., Wynn, D.C., Howard, T.J., Andreasen, M.M., 2014. Perceiving Design as Modelling: A Cybernetic Systems Perspective, in: Chakrabarti, A., Blessing, L. (Eds.), An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations. Springer London, London, pp. 133–149.
Matthiesen, S., Grauberger, P., Bremer, F., Nowoseltschenko, K., 2019. Product models in embodiment design: an investigation of challenges and opportunities. SN Appl. Sci. 1. https://doi.org/10.1007/s42452-019-1115-y.
Matthiesen, S., Grauberger, P., Hölz, K., Nelius, T., Bremer, F., Wettstein, A., Gessinger, A., Pflegler, B., Nowoseltschenko, K., Voß, K., 2018. Modellbildung mit dem C&C²-Ansatz in der Gestaltung - Techniken zur Analyse und Synthese.
Nagel, R.L., Stone, R., Hutcheson, R.S., McAdams, D.A., Donndelinger, J.A., 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, Brooklyn, New York, USA. August 3–6. ASME, pp. 273–286.
Paehler, L., Grauberger, P., Matthiesen, S., 2023. Rethinking how we describe product models in engineering design research. Preprint.
Paehler, L., Matthiesen, S., 2024. Mapping the landscape of product models in embodiment design. Research in Engineering Design. https://doi.org/10.1007/s00163-024-00433-x.
Pahl, G., Beitz, W., Wallace, K. (Eds.), 1996. Engineering Design. Springer London, London.
Palani Rajan, P.K., van Wie, M., Campbell, M., Wood, K.L., Otto, K.N., 2005. An empirical foundation for product flexibility. Design Studies 26, 405–438. https://doi.org/10.1016/j.destud.2004.09.007.
Stachowiak, H., 1973. Allgemeine Modelltheorie. Springer Verlag, Wien.
Tang, D., Zhu, R., Tang, J., Xu, R., He, R., 2010. Product design knowledge management based on design structure matrix. Advanced Engineering Informatics 24, 159–166. https://doi.org/10.1016/j.aei.2009.08.005.
Weidmann, D., Isemann, M., Kandlbinder, P., Hollauer, C., Kattner, N., Becerril, L., Lindemann, U., 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). 2017 Portland International Conference on Management of Engineering and Technology (PICMET), Portland, OR. 09.07.2017 - 13.07.2017. IEEE, pp. 1–7.
Wettstein, A., Grauberger, P., Matthiesen, S., 2021. Modeling dynamic mechanical system behavior using sequence modeling of embodiment function relations: case study on a hammer mechanism. SN Applied Sciences 3. https://doi.org/10.1007/s42452-021-04149-8.
Wilschut, T., Etman, L.F., Rooda, J.E., Vogel, J.A., 2018. Generation of a function-component-parameter multi-domain matrix from structured textual function specifications. Research in Engineering Design 29, 531–546. https://doi.org/10.1007/s00163-018-0284-9.

**Contact: Lukas Paehler**, Karlsruhe Institute of Technology (KIT), IPEK – Institute of Product Engineering, Kaiserstr. 10, 76131 Karlsruhe, Germany, Phone: +49 721 608-45034, Fax: +49 721 608-46051, lukas.paehler@kit.edu