INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.75

Identifying Factors Influencing the Design of a Suitable Knowledge Base in Product Engineering Projects

C. Kempf ✉, F. Sanke, J. Heimicke, S. Rapp and A. Albers
Karlsruhe Institute of Technology, Germany
✉ christoph.kempf@kit.edu

Abstract

During product engineering, engineers draw on existing knowledge as a basis. This knowledge is applied in design processes either by adopting elements, alternating some attributes, or changing the solution principles. While concepts for design reuse exist, the proactive design of a suitable knowledge base is still a challenge. In this paper, we show influencing factors in engineering and their influence on the knowledge base. These factors are of the areas market, company, project, and team. Based on our results, we intent to develop a support for engineers to set up the knowledge base.

Keywords: knowledge management, design reuse, reference system, engineering design, product development

1. Introduction

An iPod, a phone, an internet communicator. - Steve Jobs, 2007

2007 Steve Jobs introduced the iPhone (Kerris & Dowling, 2007). It united the MP3 player, telephone, camera, touch screen, and other functions in just one device. That shows that the *entirely new product iPhone* of 2007 was set up on already existing technical systems as a basis. This basis can be described by various reference products. The iPod, a mobile phone, and an internet communicator such as an iMac served as reference products in this context. Still, the iPhone is one of the most popular smartphones around the globe. One success factor of the iPhone could have been the availability of many well tested and well understood in-house references to draw on.

On the contrary, start-ups developing their first product cannot draw on already existing products of their own to base their development on. Thus, they often use successful designs of other companies usually used in different contexts or designs presented in scientific contexts.

A comparison of the two examples of product engineering illustrates that the situations in which product engineering takes place can be of many different types. E.g. Apple is an established successful tech company with various products already introduced to the market. They spend a huge amount on R&D every year and maintain many development teams. This enables such a company to draw back on other knowledge resources as other companies. A drastic example on the other side is a typical start-up. Being new on the market, they can seldom draw on big resources - neither regarding already existing products established on the market, nor manpower. Thus, it becomes obvious, that various engineering projects require knowledge bases designed differently to meet the requirements of the specific situation appropriately.

Since every product development process is unique and individual (Albers, 2010), we propose that unique and individual knowledge bases are needed, to meet the requirements of the specific product development project appropriately. Within this paper, we aim to analyse the correlations of factors describing the engineering situation and their influences on the respective knowledge base. On the longhand, we want to support engineers in designing an appropriate knowledge base to perform their engineering activities effectively.

2. Knowledge reuse in production engineering

Only 20% of the subsystems in a new product require fundamentally new designs. Most new challenges in product development can therefore be solved by reusing knowledge (Cross, 2007; Iyer et al., 2005; Zhang et al., 2017) agreed on this, stressing that the greater part of engineering activities is about modifying already existing designs/ solutions. However, in most engineering projects, the active reuse of knowledge is only about 30% on average (Zhang et al., 2017). Thereby, the advantages of Design Reuse like increasing cost-effectiveness and flexibility in engineering are widely agreed on in literature (Alblas & Jayaram, 2015; Corso et al., 1999; Eckert et al., 2004; Sivaloganathan & Shahin, 1999). Thus, knowledge reuse is a competitive advantage (Zhang et al., 2017). Previous projects provide a strong basis that can be drawn upon. So it is essential to make this information of completed projects available in ongoing projects (Albers et al., 2014).

The main challenges in design/ knowledge reuse are about gaining or providing suitable information for the current engineering task (Iyer et al., 2005; Shahin et al., 1999; Sivaloganathan & Shahin, 1999). Especially the identification of suitable knowledge/ designs seems to be a problem in practice as engineers mainly draw on their own experience or known projects as sources (Ahmed et al., 2003).

The Case-based Reasoning approach and C-K Theory are approaches to search for references or creative solutions to similar problems (Hatchuel et al., 2004; Maher & Garza, 1997). Breaking down the complex engineering task, the knowledge space - K (knowledge/ experience) of the engineers is searched for analogies which form the basis for new solutions/ concepts (concept space - C).

Gero (1990) and Eckstein and Henrich (2008) both notice that context is of high importance in knowledge reuse (Eckstein & Henrich, 2008; Gero, 1990). Describing the user's information need more precisely by its context is useful because "an engineer in the early phases in a development process might look for general documents whereas later phases demand more specific documents in terms of the documents' degree of maturity" (Eckstein & Henrich, 2008). With a contextual search, not only the text of the query of the user is taken into account, but also the dependencies between different documents, leading to more detailed search results (Eckstein & Henrich, 2008).

Albers et al. (2015) introduced a universal approach, the model of PGE - Product Generation Engineering, to describe any kind of product engineering project. Thereby, he aims at offering a solid basis for research on engineering projects as well as the development of methods supporting engineering projects.

The model of PGE has two basic assumptions. First, every product engineering project is based on *reference products*, such as already existing solutions, products, or concepts. Thus, product development can be seen as the development of a new generation based on references. These reference products can originate in the direct predecessor generation of the product, products of competitors, different industries, or even university research/ R&D projects. Second, the development of the new product generation of a subsystem can be described by three types of variation; *carryover variation (CV)*, *embodiment variation (EV)*, and *principle variation(PV)*. (Albers et al., 2015)

With the *reference system*, Albers et al. (2019) added another element to the model of PGE, describing the relationship of reference products and new product generations in a more formalized manner (Figure 1). Thus, the reference system contains all *reference system elements (RSE)* and their interrelations. Reference system elements can be retrieved from socio-technical systems or their associated documentation. The reference system is the starting point for developing new product generations by conducting CV, EV, and PV.

Reference system elements can be characterized by their origin, which can be external (same or different branch, research) or internal (company, development team). Impact factors of the reference system on development targets are origin, maturity level and complexity of RSE. The reference system can be characterized by these quantities among others.

For mapping and thus researching engineering processes and activities, the iPeM - integrated Product engineering Model can be used. The iPeM consists of layers for the integrated modelling of the

https://doi.org/10.1017/pds.2022.75 Published online by Cambridge University Press

development of various product generations, the validation system, production system, and strategy. These layers have to be considered in an integrated way due to their strong connections in the targeted objectives, pursued object systems and used operation systems.

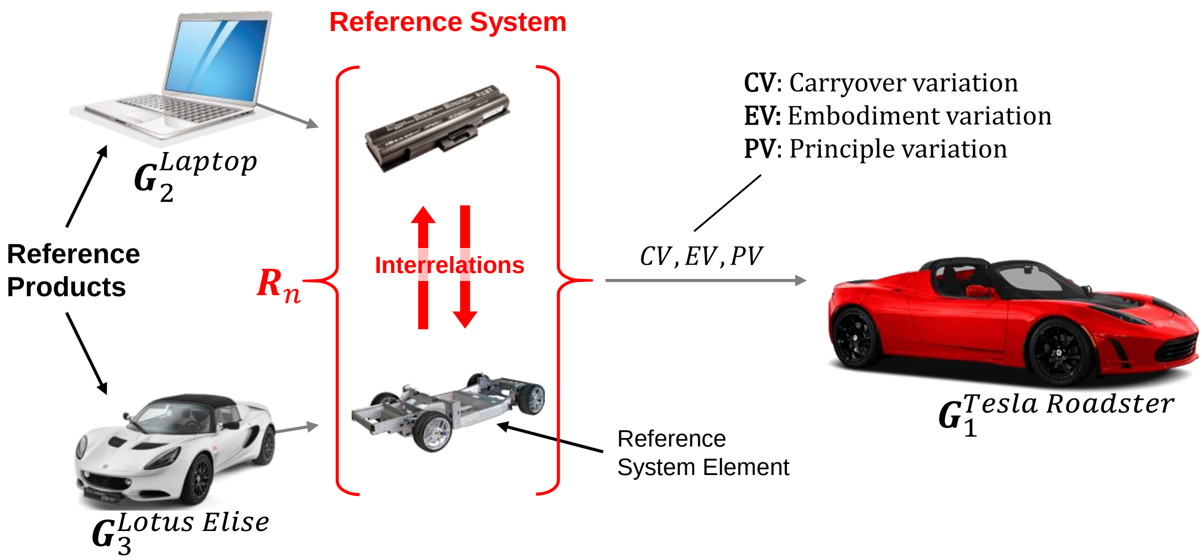

Figure 1. The reference system in the model of PGE - Product Generation Engineering (Albers et al., 2019)

3. Research objective and research approach

As illustrated in the two opening examples, different situations in engineering require differently designed reference systems to support engineers in conducting engineering activities appropriately. The reference system within the model of PGE - Product Generation Engineering offers a solid foundation to research the characteristics needed in a specific reference system in a specific engineering situation. We believe this will provide insights to develop methodical support for engineers to design a suitable reference system actively according to their situation and engineering activities. Therefore, the main goal of this paper is to identify the correlations between the engineering situation and the design of an appropriate reference system. To reach this goal, the following research questions are discussed within this paper:

- Which factors in the context of product engineering influence the reference system?
- How can the correlations between the identified influencing factors and the reference system or its elements be described?

To answer these research questions, we chose a literature-based approach analysing publications of the contexts of knowledge reuse and PGE, case studies of product engineering projects and process models used in product engineering. We analysed these publications regarding factors of the engineering situation such as the context of the company and competition, engineering activity, or team related and correlated them with characteristics of the references that were used in these specific or general descriptions.

As illustrated in Figure 2, we followed an approach of three focus points. First, we aimed at analysing the literature on knowledge/ design reuse. Therefore, we conducted a literature review based on the publication introducing the reference system by Albers et al. (2019). Serving as a starting point, we used this paper for tracing back the mentioned references. Thereby, we identified factors influencing the reference system as well as characteristics of the reference system or its elements that are influenced.

In a second step, we analysed various case studies describing product engineering projects. Therefore, we first collected case studies in the context of the model of PGE. Subsequently, we conducted a systematic literature review approach to collect additional case studies described in the literature. We

https://doi.org/10.1017/pds.2022.75 Published online by Cambridge University Press

performed this review using the scientific database *Scopus* limiting the results to papers using the English language. The search space of the review is described with the following search string:

(TITLE-ABS-KEY (product AND development) OR TITLE-ABS-KEY (product AND engineering)) AND TITLE-ABS-KEY (case AND study) AND TITLE-ABS-KEY (reuse AND knowledge) AND TITLE-ABS-KEY (reuse AND design).

The 173 results of the search were narrowed down to the field of engineering with the help of a filter. Publications discussing theoretical cases, methods or literature reviews were excluded. In addition, we only considered peer-reviewed publications, i.e. *journals* and *conference papers*:

AND (SUBJAREA(engi)) AND (LIMIT-TO(SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p"))

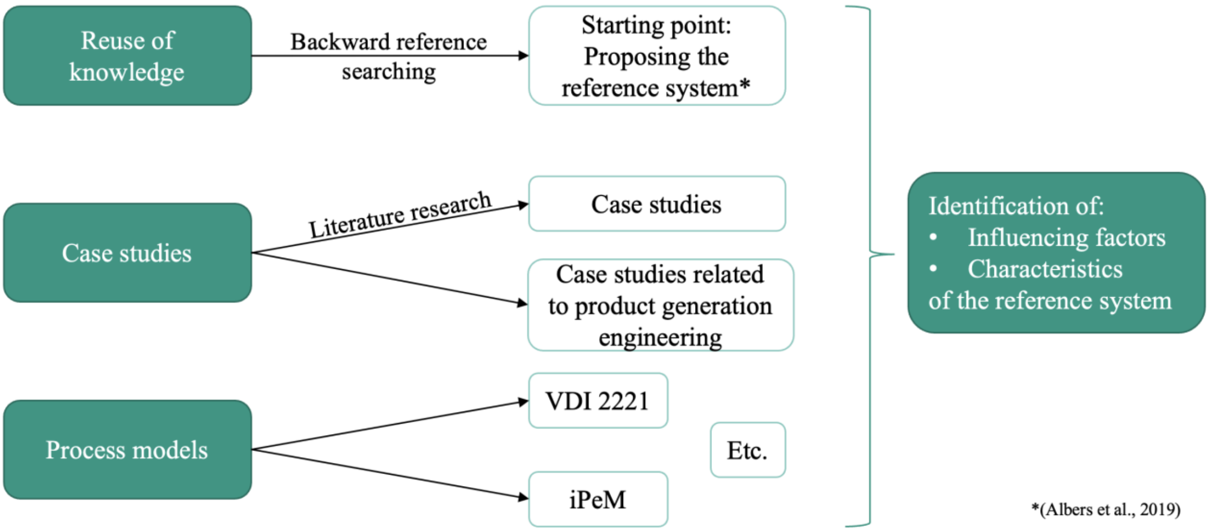

Figure 2. Structure of the literature research

To close our review, we analysed process models commonly used in product engineering in a third step. The aim is to check what phases or activities, require what types of reference system elements.

4. Observations from literature research

Based on the presented methodology, we analyzed scientific publications regarding factors influencing the reference system and its elements as well as their influences, retrospectively. In the following, we present the results clustered by the used research approaches and illustrate, how we gained the results. Hereby, we do provide examples of how the individual factors were derived from the various sources. All deducted influencing factors are given in Table 1.

Influencing factors mentioned in the knowledge reuse literature

Corso et al. (1999) state, the high degree of product individualization in the automotive sector requires a high standardization at both, the product architecture and component level. They state, that a high product variety is achieved by modular product architecture. (Corso et al., 1999) Thus, we concluded, that the industry influences the product architecture and standardization of the components but has no influence on the reference system directly.

https://doi.org/10.1017/pds.2022.75 Published online by Cambridge University Press

Table 1. Overview of all identified influencing factors and influenced variables with their specific value in the context of the reference system

Source		Influencing factor	Value	Influenced variable	Value
Influencing factors mentioned in the knowledge reuse literature					
(Corso et al., 1999)	[1]	Product variety	high	Structure of the product architecture	modular
		Industry	-	Product life cycle duration	-
		Industry	-	Structure of the product architecture	-
		Industry	Automotive	Standardisation level of components	high
(Baxter, Gao, & Roy, 2008)	[2]	Production volume	high	Standardisation level of components	high
(Alblas & Jayaram, 2015)	[3]	Industry	-	Market uncertainty	-
		Market uncertainty	high	Structure of the product architecture	modular
		Market uncertainty	high	Development time	short
(Sivaloganathan & Shahin, 1999)	[4]	Activities of product engineering	-	RSE type	-
(Wyatt et al., 2009)	[5]	Number of variants	-	Structure of the product architecture	-
		Legal situation	insecure	Structure of the product architecture	modular
		Legal situation	insecure	Origin of the designer	internal
		Product generation	G>1	Level of detail of RSE	high
(Ettlie & Kubarek, 2008)	[6]	Development time	short	Origin of RSE	internal
(Markus, 2001)	[7]	Experience of the designer	-	RSE type	-
(Wouters & Kerssens-Van Drongelen, 2004)	[8]	Structure of the product architecture	modular	Standardisation level of components	high
		Standardisation level of components	high	Level of detail of RSE	high
		Standardisation level of components	high	Maturity level of RSE	high
		Structure of the product architecture	modular	Origin of RSE	internal
		Market uncertainty	high	Structure of the product architecture	modular
		Legal situation	insecure	Structure of the product architecture	modular
		Number of cooperating companies	high	Homogeneity of the reference system	heterogeneous
Influencing factors mentioned in the case study literature					
(Vezzetti et al., 2011)	[9]	Origin of the designer	-	Terminology of the reference system	-
(Hernandez et al., 2011)	[10]	Industry	-	Legal situation	-
(Zhang et al., 2017)	[11]	Origin of the designer	-	Terminology of the reference system	-
(Sassanelli et al., 2021)	[12]	Homogeneity of the development team	heterogeneous	Homogeneity of the reference system	heterogeneous
		Origin of the designer	-	Homogeneity of the development team	-
(Pakkanen et al., 2019)	[13]	Industry	Ship building	Structure of the product architecture	modular
		Product generation	G>1	Origin of RSE	internal
		Product generation	G>1	Homogeneity of the reference system	homogeneous
(Albers et al., 2019)	[14]	Protection status	Licence granted	Approval for use	open
		Homogeneity of the development team	heterogeneous	Homogeneity of the reference system	heterogeneous
		Standardisation level of components	high	Level of detail of RSE	high
		Product generation	G>1	Level of detail of RSE	high
		Product generation	G>1	Origin of RSE	internal
		Origin of RSE	internal	RSE type	model-based
(Albers et al., 2017)	[15]	Corporate partnership	cooperation	Number of cooperating companies	-
		Number of cooperating companies	cooperation	Homogeneity of the development team	heterogeneous
		Origin of the designer	external	Origin of RSE	external
		Protection status	patented	Approval for use	locked
(Albers et al., 2020)	[16]	Development time	short	Origin of RSE	internal
(Pfaff et al., 2021)	[17]	Product generation	G1	Origin of RSE	external
		Professional experience of the designer	low	Homogeneity of the development team	heterogeneous
		Type of company	-	Number of cooperating companies	-
(Albers et al., 2016)	[18]	Product life cycle duration	short	Origin of RSE	internal
Influencing factors mentioned in product engineering process models					
(VDI, 2019b)	[19]	Type of company	SME	Number of variants	high

https://doi.org/10.1017/pds.2022.75 Published online by Cambridge University Press

The design model according to Sivaloganathan and Shahin (1999) shows different activities of product engineering including typical outcomes. Analyzing his statements, we concluded, that each product engineering activity requires different types (e.g. requirements or detailed designs) of reference system elements.

Wyatt et al. (2009) discuss a manufacturer of diesel engines faces different customer preferences which lead to a high number of product variants. They also state customers want to be independent of environmental protection laws. According to them, this forces the company to keep the external interfaces constant. To sum up, the high number of product variants and the insecure legal situation lead the company to a modular product structure. To meet the insecure legal situation, a design team for an electronic control system and exhaust after-treatment is centralized at the parent company level. Based on this description, we concluded that the unclear legal situation influenced the origin of the designer included in the design team.

Following Ettlie and Kubarek (2008), involving suppliers and customers in the development process of new products or services will slow down the process. A search for internal reuse sources can therefore save time. Thus, a required short development time can imply favouring internal reference system elements.

A further case is the development of an electric toothbrush. Commonalities also contribute to the standardization of the product architecture: The charging unit is the same across all product variants (Wouters & Kerssens-Van Drongelen, 2004). We concluded, that a modular product architecture contributed to the use of highly standardized components, which lead to a high detail and maturity level of used reference system elements. Also, the origin of the charging unit can be interpreted as an internal reference system element.

Influencing factors mentioned in the case study literature

Following relation have been found in the second part of the literature research, which lays effort on case studies.

According to Baxter et al. (2008), in variant-design or evolutionary design, many requirements remain the same as with the previous product generation. Thus, we concluded, a higher product generation can lead to higher maturity levels of requirements specification.

Technical specifications are not normally formulated in a standardized way (Vezzetti et al., 2011) because designers prefer a different presentation or transfer of knowledge depending on their role in the product life cycle (Zhang et al., 2017). Thereby, the origin (discipline/ branch and experience) of the designers influences the terminology of the reference system.

To realize a new solution, the heterogeneity of the development team is important (Sassanelli et al., 2021). We concluded this can increase the heterogeneity of the reference system due to the team members diverse fields of expertise and experiences.

An example in the context of the model of PGE is the development of new technology for the processing of particle foams using frequency technology. Hereby a patent of a company from another industry is used. (Albers et al., 2019) Since the company grants usage of their patent, its technical concept is transferable from the reference system to the system of objects. Thus, we concluded, that the protection status determines the approval to use references unaltered. A frame according to a standard is used instead of the frame of the previous generation (Albers et al., 2019). The usage of the frame of the predecessor would have resulted in a model-based type of RSE since a CAD model is already available. Hereby, we concluded that the origin of an RSE can determine the type of the RSE (e.g. model-based or document-based).

Another example is the development of the dual-mass flywheel. During its development, a unique spring mechanism was patented. This forced competitors to find a different solution for their product with the same function (Albers et al., 2017). Thus, we concluded that the protection status of references can define the freedom to use the reference system element.

Furthermore examined the start-up company *kamedi*. The development in this start-up environment is characterized by only external sources, leading to reference system elements of external origin since no previous product generation is available. Moreover, the lack of empirical knowledge from the field on the part of the founders can lead to the involvement of external partners (Pfaff et al., 2021). By this analysis of start-up environments, we concluded that the type of company (e.g. start-up or established group) can influence the origin of reference system elements as well as the heterogeneity of the development team.

Influencing factors mentioned in product engineering process models

To complete the findings, we analyzed process models.
The VDI-guideline 2206 (2004) states that in the activity "systems design", a search for principles and solution elements should be performed to fulfil sub-functions. This can be seen as a search for reference system elements. Additionally, VDI-guideline 2221 (2019a) deals, among other subjects, with clarifying and specifying the problem or task. These activities include gathering all available information, which also can be interpreted as an active search for reference system elements. The guideline (2019b) states that especially small and mid-size enterprises develop products, which can be characterized by middle to high complexity and a high number of variants. Besides contextual factors in product design are presented (VDI, 2019b). However, these factors cannot be transferred directly as influencing factors of the reference system without additional validation.

The factors influencing the reference system - overview

Analyzing the identified influencing factors as well as the variables influenced, we saw that not all of them influence the reference system or characteristics of the reference system directly. As illustrated in Figure 3, we distinguished the two groups of direct and indirect influencing factors to sort these relations. Direct influencing factors have a direct influence on the characteristics of the reference system, whereas indirect factors only influence other factors.

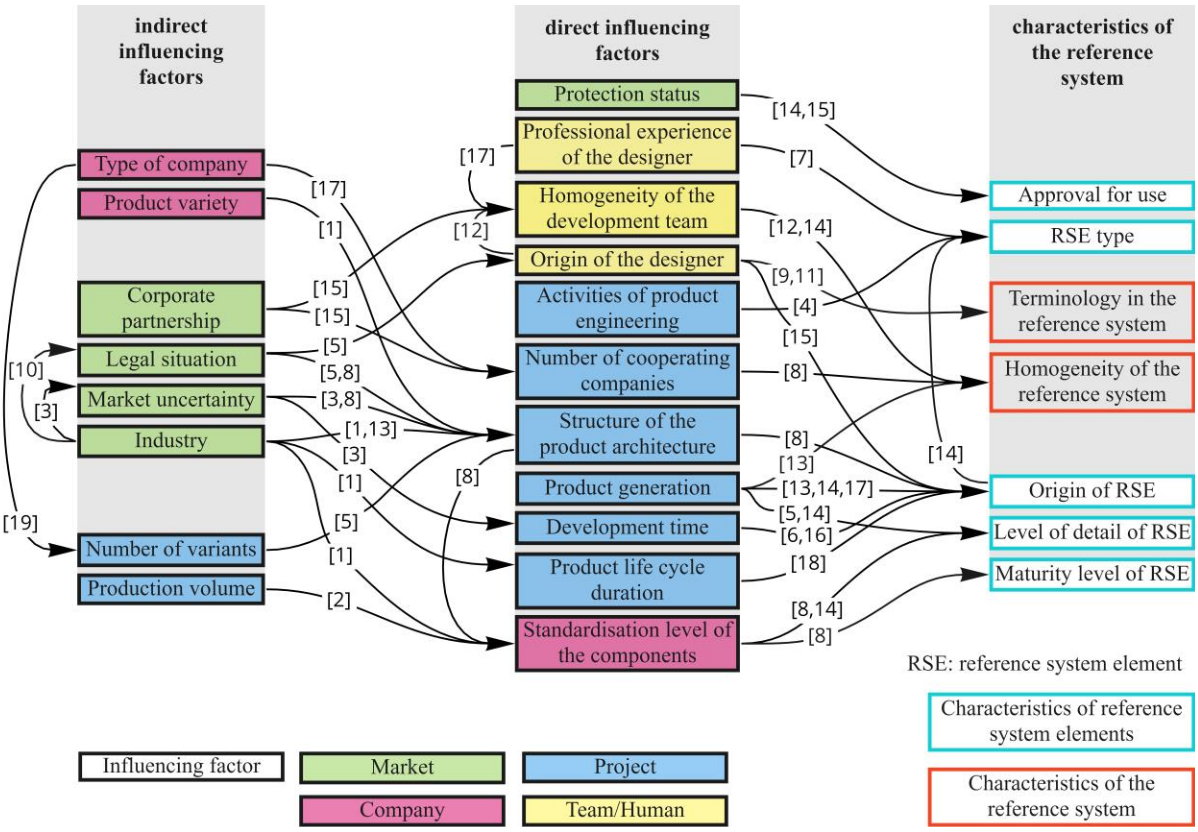

Figure 3. Interrelation model of influencing factors and characteristics of the reference system. Specific values of the factors and characteristics are explained in table 1 and within chapter 4.

In a further step, we categorized the influencing factors using the categories of the contextual factors in product design according to VDI-guideline 2221 (2019b). Thus, factors are labelled as market-, company-, project-, and team/human-related. This made it apparent that factors in the market and

https://doi.org/10.1017/pds.2022.75 Published online by Cambridge University Press

company categories tend to be indirect factors, while factors in the project and team/ human groups are more often direct influencing factors.
Starting from the known characteristics of the reference system elements (origin maturity level, and complexity), we added the characteristics of *approval for use*, *type*, and *level of detail of reference system elements* as influenced characteristics based on our findings. On the other hand, the complexity of the reference system element did not appear as an RSE characteristic influenced by the identified factors. Some factors have a more general influence. These influence characteristics of the reference system in total. Therefore, we introduced *terminology in the reference system* and *homogeneity of the reference system*.

5. Conclusion

The term reference system is not commonly used in literature. Therefore, we conducted the literature review in a general way to get an overview of the topic. Thus, we had to interpret the statements in the context of knowledge respective design reuse and to set it into the context of the reference system. Furthermore, a significant part of the literature review was based on research of the authors' institute. Therefore, a broader (systematic) literature review offers the potential to further enhance the derived model.
Based on the given results, it is evident that influences on the characteristics of the reference system and its elements can have diverse origins. Thus, specific development situations as combinations of e.g. the context and position of the company in the market (start-up, first mover, etc.), industry (automotive, medical, etc.), current product engineering activity (detecting ideas, modelling embodiment, etc.), and team composition (experienced, background, etc.) have diverse requirements on a well-designed reference system. The importance of the category team/human confirms the socio-technical background and context of the reference system, whereas project-related factors are most present in our model. Within this paper, we demonstrated the existence of interrelations between the development situation and the reference system. However, that does not suffice for general statements of how to adjust or design the characteristics of the reference system and its elements but provides possible best practices. This is assured as results show that different but also the same states of the influencing factors can drive the reference system and its elements in the direction of the same or different characteristics. For instance, the origin of reference system elements depends on a variety of influencing factors. Here, we can conclude that the knowledge of the state of just one influencing factor does not suffice to pick the appropriate value of the characteristics of the reference system or its elements, but all factors influencing one characteristic have to be considered as a system. The created model (Figure 3) provides an orientation on how to classify influencing factors and which characteristics are influenced by which factors. Nevertheless, we expect our model to be incomplete and thus, each development situation should be analysed carefully to derive possible implications on the references system and adapt the interrelation model to the specific case. This becomes evident as obvious correlations or influencing factors were not mentioned in the literature. One example is the corporate strategy. Introducing a new product into the market as the first company, using the first-mover strategy will imply using external RSE from other industries or research, mainly. The possible implication of the current activity of product engineering on the level of detail of RSE is another good example. E.g. RSE on a very shallow level of detail (images, effects of nature, etc.) might suffice to stimulate creativity in ideation while modelling embodiment is better supported by detailed 3-D models.

6. Outlook

With the presented work, we were able to describe the interrelations of various influencing factors of the development situations on the reference system. In the following work, we aim to extend this model to a methodical support, by giving advice to engineers on how to design a suitable and specific reference system meeting the requirements of the current development situation. Therefore, the presented model of interrelations has to be extended e.g. by a broader literature review or surveys to identify further influencing factors.

In the following, we intend to identify the implications of various states of the influencing factors on the characteristics of the reference system or its elements. Hereby, one challenge will be considering the emergence effects of different influencing factors on the same characteristics of the reference system. Thereby, we aim at providing advice on how the reference system could be designed and which RSE could be gathered to set up a suiting reference system for the given development situation. We believe this will help in knowledge reuse in engineering projects and thus lead to more efficient product development and consequently, more sustainable use of resources like development time, or materials.

Acknowledgement

The research documented in this manuscript has been funded by the German Research Foundation (DFG) within the International Research Training Group 'Integrated engineering of continuous-discontinuous long fibre reinforced polymer structures' (GRK 2078). The support by the German Research Foundation (DFG) is gratefully acknowledged. The author is responsible for the content of this publication.

References

Ahmed, S., Wallace, K. M., & Blessing, L. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, *14*, 1–11.

Albers, A. (2010). Five Hypotheses about Engineering Processes and their Consequences. *Proceedings of the TMCE 2010, Ancona, I, April 12-16,* 2010.

Albers, A., Bursac, N., & Rapp, S. (2017). PGE – Produktgenerationsentwicklung am Beispiel des Zweimassenschwungrads. *Forschung im Ingenieurwesen*, *81*, 13–31. https://doi.org/10.1007/s10010-016-0210-0

Albers, A., Bursac, N., Urbanec, J., Lüdcke, R., & Rachenkova, G. (2014). Knowledge management in product generation development—An empirical study. *25th Symposium Design for X, DFX 2014, Bamberg; Germany, 1. October 2014 through 2. October 2014. Ed.: D. Krause*, 13–24.

Albers, A., Bursac, N., & Wintergerst, E. (2015). Produktgenerationsentwicklung—Bedeutung und Herausforderungen aus einer entwicklungsmethodischen Perspektive. *Stuttgarter Symposium für Produktentwicklung (SSP) : Stuttgart, 19. Juni 2015 ; Hrsg.: H. Binz*, 1–10.

Albers, A.; Haug, F.; Heitger, N.; Arslan, M.; Rapp, S. & Bursac, N.: Produktgenerationsentwicklung - Praxisbedarf und Fallbeispiel in der auto-mobilen Produktentwicklung. *In: J. Gausemeier (Hrsg.): Vorausschau und Technologieplanung. 12. Symposium für Vorausschau und Technologie-planung 2016a. Berlin. Paderborn, S. 227–242.*

Albers, A., Rapp, S., Spadinger, M., Richter, T., Birk, C., Marthaler, F., Heimicke, J., Kurtz, V., & Wessels, H. (2019). The Reference System in the Model of PGE: Proposing a Generalized Description of Reference Products and their Interrelations. *Proceedings of the 22nd International Conference on Engineering Design (ICED19), Delft, The Netherlands*, *5-8 August* 2019, *1*(1), 1693–1702. https://doi.org/10.1017/dsi.2019.175

Albers, A., Reiss, N., Bursac, N., & Richter, T. (2016b). IPeM – Integrated Product Engineering Model in Context of Product Generation Engineering. *26th CIRP Design Conference*, *50*, 100–105. https://doi.org/10.1016/j.procir.2016.04.168

Alblas, A., & Jayaram, J. (2015). Design resilience in the fuzzy front end (FFE) context: An empirical examination. *International Journal of Production Research*, *53*(22), 6820–6838. Scopus. https://doi.org/10.1080/00207543.2014.899718

Baxter, D., Gao, J., Case, K., Harding, J., Young, B., Cochrane, S., & Dani, S. (2008). A framework to integrate design knowledge reuse and requirements management in engineering design. *ICMR2005: Third International Conference on Manufacturing Research*, *24*(4), 585–593. https://doi.org/10.1016/j.rcim.2007.07.010

Corso, M., Muffatto, M., & Verganti, R. (1999). Reusability and multi-product development policies: A comparison of approaches in the automotive, motorcycle and earthmoving machinery industries. *Robotics and Computer-Integrated Manufacturing*, *15*(2), 155–165. Scopus. https://doi.org/10.1016/S0736-5845(99)00010-1

Cross, A. (2007). Engineering Design Methods—Strategies for Product Design. Wiley.

Eckert, C. M., Clarkson, P. J., & Zanker, W. (2004). Change and customisation in complex engineering domains. *Research in Engineering Design*, *15*, 1–21.

Eckstein, R., & Henrich, A. (2008). *An integrated context model for the product development domain and its implications on design reuse*. 761–768. Scopus. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84861479414&partnerID=40&md5=d6a3cdd0b4066c49013cade704b7d94c

https://doi.org/10.1017/pds.2022.75 Published online by Cambridge University Press

Ettlie, J. E., & Kubarek, M. (2008). Design reuse in manufacturing and services. *Journal of Product Innovation Management*, *25*(5), 457–472. Scopus. https://doi.org/10.1111/j.1540-5885.2008.00314.x
Gero, J. S. (1990). Design Prototypes: A Knowledge Representation Schema for Design. *AI Magazine*, *11*(4), 26–36.
Hatchuel, A., Masson, P. L., & Weil, B. (2004). C-K Theory in Practice: Lessons from Industrial Applications. *DS 32: Proceedings of DESIGN* 2004, 245–258.
Iyer, N., Jayanti, S., Lou, K., Kalyanaraman, Y., & Ramani, K. (2005). Three-dimensional shape searching: State-of-the-art review and future trends. Computer-Aided Design 2005, *37*(5), 509–530. https://doi.org/10.1016/j.cad.2004.07.002
Kerris, N., & Dowling, S. (2007, January 9). *Apple Reinvents the Phone with iPhone*. https://www.apple.com/newsroom/2007/01/09Apple-Reinvents-the-Phone-with-iPhone/
Maher, M. L., & Garza, A. G. de S. (1997). Case-Based Reasoning in Design. *IEEE Expert*, *12*, 34–41.
Pfaff, F., Kubisch, J., Rapp, S., & Albers, A. (2021a). Characterizing Product Development Processes in Start-ups – an Empirical Study. ISPIM Conference Proceedings, The International Society for Professional Innovation Management (ISPIM), Berlin, Germany, 1-16. 10.5445/IR/1000137421
Pfaff, F., Rapp, S., & Albers, A. (2021b). Modelling and Visualizing Knowledge on the Reference System and Vibrations based on the Model of PGE – Product Generation Engineering for Decision Support. *Proceedings of the Design Society*, *1*, 2167–2176. https://doi.org/10.1017/pds.2021.478
Sassanelli, C., Da Costa Fernandes, S., Rozenfeld, H., Mascarenhas, J., & Terzi, S. (2021). Enhancing knowledge management in the PSS detailed design: A case study in a food and bakery machinery company. *Concurrent Engineering Research and Applications*. Scopus. https://doi.org/10.1177/1063293X21991806
Shahin, T. M. M., Andrews, P. T. J., & Sivaloganathan, S. (1999). A design reuse system. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *213*(6), 621–627. https://doi.org/10.1243/0954405991517065
Sivaloganathan, S., & Shahin, T. M. M. (1999). Design reuse: An overview. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *213*(7), 641–654. https://doi.org/10.1243/0954405991517092
VDI. (2004). VDI-Richtlinie 2206: Entwicklungsmethodik für mechatronische Systeme. Beuth Verlag.
VDI. (2019a). VDI-Richtlinie 2221 Blatt 1: Entwicklung technischer Produkte und Systeme—Modell der Produktentwicklung. Beuth Verlag.
VDI. (2019b). VDI-Richtlinie 2221 Blatt 2: Entwicklung technischer Produkte und Systeme—Gestaltung individueller Produktentwicklungsprozesse. Beuth Verlag.
Vezzetti, E., Moos, S., & Kretli, S. (2011). A product lifecycle management methodology for supporting knowledge reuse in the consumer packaged goods domain. *Computer-Aided Design*, *43*(12), 1902–1911. https://doi.org/10.1016/j.cad.2011.06.025
Wouters, M. J. F., & Kerssens-Van Drongelen, I. C. (2004). *Improving cross-functional communication about product architecture*. *2*, 561–565. Scopus. https://www.scopus.com/inward/record.uri?eid=2-s2.0-17644408091&partnerID=40&md5=72701a3e4253338070733317a1452df0
Wyatt, D. F., Eckert, C. M., & Clarkson, P. J. (2009). *Design of product architectures in incrementally developed complex products*. 167–178. Scopus. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84859252956&partnerID=40&md5=bf8aaa661537ea4ab161f8b00f7e7dc4
Zhang, C., Zhou, G., Lu, Q., & Chang, F. (2017). Graph-based knowledge reuse for supporting knowledge-driven decision-making in new product development. *International Journal of Production Research*, *55*(23), 7187–7203. Scopus. https://doi.org/10.1080/00207543.2017.1351643