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Implications of Creating Solution Concepts Based on the Use of References

M. Schlegel ✉, F. Pfaff, S. Rapp and A. Albers

Karlsruhe Institute of Technology, Germany

✉ michael.schlegel@kit.edu

Abstract

The use of already validated systems as references for the development of solution concepts offers the potential to increase process efficiency. It is important to understand how the use of references impacts the development of solution concepts. Therefore, the representation of solution concepts in an engineering project of two student cohorts are analyzed and compared. The first cohort is provided with few and the second cohort with extensive references. The results of the study show that the increased use of references leads to a higher share of embodiment and specific challenges.

Keywords: design knowledge, decision making, design process, communication, product generation engineering (PGE)

1. Introduction

In industrial practice, products are developed based on references. This observation is one of the core concepts of the model of PGE - Product Generation Engineering according to Albers (2015).
The description of product development processes as reference-based product generation engineering enables the development of demand-oriented method and process support for designers. An important subject area is to understand and support the use of references in the development process (Albers *et al.*, 2019). This contribution investigates how developers deal with references in concept development, what impact the use of references has on solution representations, and what challenges arise. For this purpose, data were collected and analyzed in two student cohorts of the Live-Lab *Mechatronic Systems and Products (MSuP)* at the Karlsruhe Institute of Technology (KIT). The LiveLab MSuP is a research environment that makes it possible to explore methods and processes of product development in a close to real complex development process in seven teams with around 100 engineering students.
In a previous study in the 2018/19 student cohort of the Live-Lab MSuP, the use of references was investigated over the entire development process. A selected set of student solutions for subsystems from the previous year were provided to the students. The study showed that the students used references after the solution concept was finished and checked. They checked whether a subsystem reference fulfilled the functional requirements and could be carried over or not and had to be varied. (Albers *et al.*, 2018b)
In this contribution, the representation of the solution concepts of the 2019/20 and the 2020/21 cohort are compared. The 2019/20 student cohort were provided with selected references from the previous year and no methodical support for reference-based solution concept development, which makes the initial situation comparable to 2018/19. The 2020/21 cohort were provided with all partial results from the previous year and support for the systematic use of references. In Figure 1, exemplary representations of solution concepts of two teams from the examined years are contrasted exemplary.

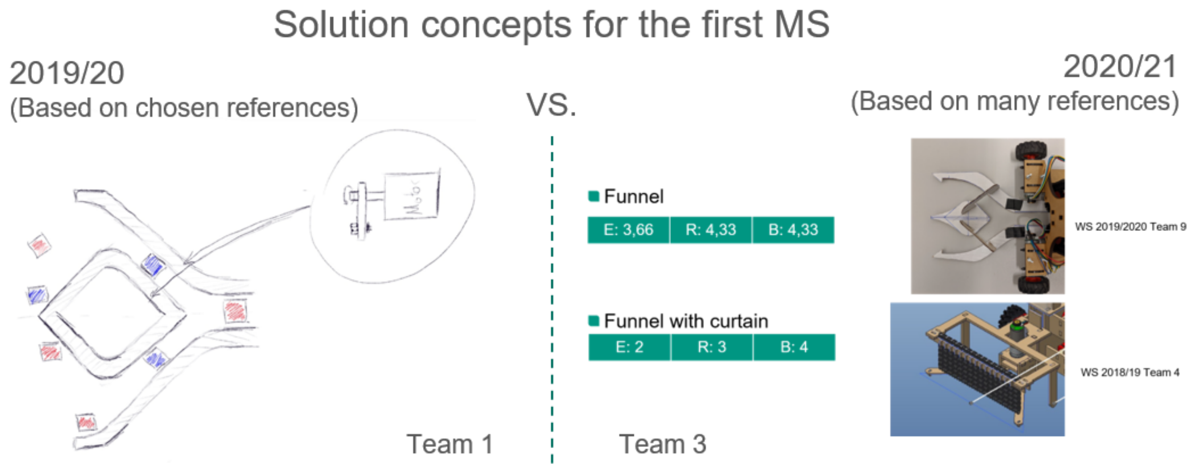

Figure 1. Solution concepts of the teams of the two cohorts for the first milestone of the Live-Lab MSuP. E: Effort, R: Risk, B: Benefit WS: Winter semester MS: Milestone. The purpose of the shown systems is to collect cubes autonomously driving on a playing field in order to pass them later to a second subsystem.

2. State of the art

2.1. Use of References in Product Development

Multiple approaches model the relationship between existing and new designs and aim at the systematic reuse of knowledge. Design Reuse is a process of reusing existing design artefacts in new designs which aims at reusing the knowledge of developers and companies contained in past products (Sivaloganathan and Shahin, 1999). The widespread term Engineering Change Management includes methods and processes to minimize negative effects of engineering changes, to predict the impact of engineering changes and to enhance flexibility in design (Alblas and Jayaram, 2015). The C-K-theory introduced by Hatchuel and Weil (2003) models the knowledge of developers in the "Knowledge-Space" (K-Space) in which all possible elements of knowledge can be stored. The model of PGE - Product Generation Engineering according to Albers describes the use of internal and external design knowledge through references. The relationship between existing references and the product generation under development is described systematically and at different levels of abstraction (Albers *et al.*, 2019), which is why the model of PGE is used as the descriptive model in this contribution.

2.1.1. The model of PGE - Product Generation Engineering

The model of PGE – Product Generation Engineering according to Albers is a descriptive model that describes product development with the new perspective of product generation engineering and is based on two fundamental hypotheses (Albers *et al.*, 2015; Albers *et al.*, 2019):

- Each product development is based on a reference system R_n (see figure 2). Reference system elements (RSE) originate from existing or already planned socio-technical systems and the associated documentation. RSE can be subsystems of predecessor, competitor, or even industry-external products and concepts from research.
- The subsystems of a new Product Generation G_n are developed based on reference system elements exclusively by three types of variation: Principle variation (PV), embodiment variation (EV) and carryover variation (CV).

In the case of a principle variation (PV), the solution principle is changed compared to the reference system element. A principle variation is always accompanied by a change in the number of working surface pairs (WSP) and channel and support structures (CSS). In the case of embodiment variation (EV), the solution principle from a reference system element (RSE) is retained and the embodiment is changed. The amount of WSP and channel and CSS is retained. In a carryover variation CV, the embodiment and solution principle of the subsystems are adopted from a reference system element and

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remain unchanged. Only the interfaces can be adapted according to the requirements of the system integration. WSP and CSS remain largely unchanged. Mathematically, the new product generation can be described as the sum of its subsystems developed with the three variation types (Albers and Wintergerst, 2014; Albers *et al*. 2015; Albers *et al.*, 2019)

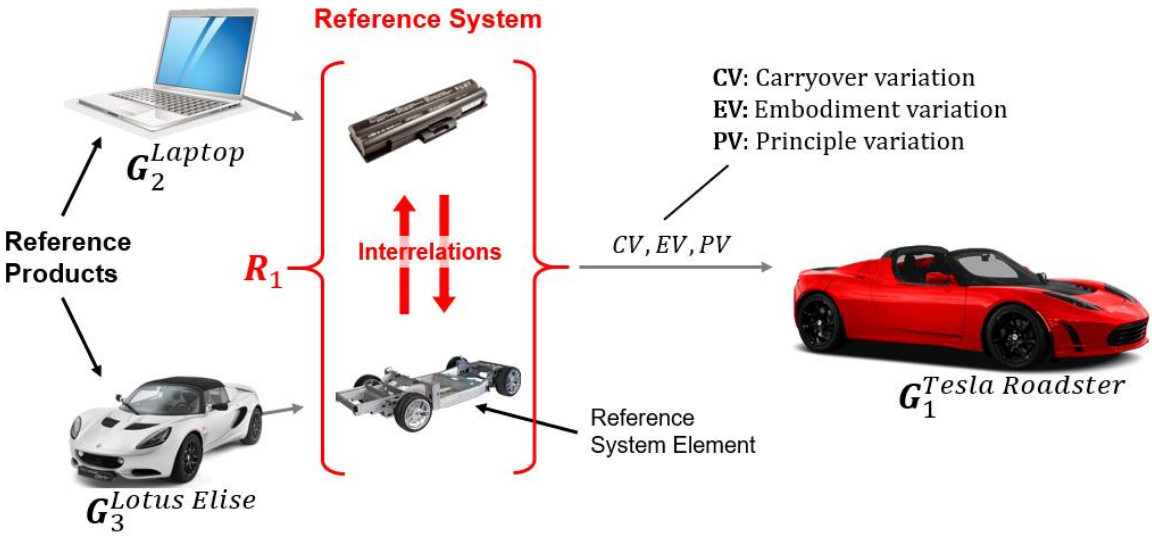

Figure 2. The reference system in the model of PGE (Albers *et al*., 2019). In the development of the Tesla roadster, the chassis of the Lotus Elise was carried over (CV). The battery cells from the reference product laptop were integrated with a new configuration (EV).

The type of variation and the characteristics of RSE such as origin, complexity and maturity level are key factors for development risk, cost and innovation potential. A higher proportion of PV and EV share as well as the use of external RSE result in increased development risk and the tendency of higher costs due to additional validation and design activities. (Albers *et al.*, 2017; Pfaff *et al.*, 2021)

2.2. Solution concepts in the product development process

The embodiment of a product is defined by its geometric and material design parameters and determined in the design process. The basis for designing a product is the solution concept developed at the beginning of the product development process. (Matthiesen, 2021)

In industrial practice, the activities of concept development and its validation often take place in a separate phase, which is completed by a concept milestone (VDI, 2019a). The result of the concept development activities - the solution concept - is essential for the success of the further development process (Gericke *et al.*, 2021). It may be necessary to adjust the solution concept as the development process progresses with new insights from the iterative analysis and synthesis process (Matthiesen, 2021). The term *concept* can be defined in different ways. In this contribution, the term concept is understood as an intermediate result in the development process that emerges from certain activities and that itself includes and links certain partial results.

2.2.1. Current understanding of a solution concept

Solutions are synthesized and modelled at different levels of abstraction in the product development process. From the abstract to the concrete, Ehrlenspiel and Meerkamm propose the levels of function (functional solution possibilities), physics (principle, physical solution possibilities), embodiment (design solution possibilities), and production (solution possibilities of the manufacturing implementation) (Ehrlenspiel and Meerkamm, 2017). Albers et al., 2018a propose customer-experienceable product attributes as the most abstract level of product description for an early stage in the product development process (Albers *et al.*, 2018a). Solution concepts are as an intermediate result at least partially solution-open. To what extent a solution concept already specifies the final design

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solution suitable for production is not clearly defined. Certain partial results can be specified as part of the solution concept.

According to Gericke et al. (2021), a solution concept describes the functions a product has to fulfil to meet its requirements, boundary conditions and objectives and the function carriers which realize these functions. The hierarchical breakdown of the functions that a product must fulfil into sub-functions results in the functional structure of a product. The function carriers can be understood as technical systems which themselves can be divided into subsystems, elements and their interactions according to Ropohl (2009). The solution concept initially specifies the (sub)systems, their elements and their interactions which realize the functions, whereby it links the functional structure and the system structure (VDI, 2019b).

Another partial result included in the solution concept is the effective structure or principle solution, which defines the physical effective principles required to realize the functions and how they are linked (VDI, 2019b; Gericke *et al.*, 2021). These effects occur on working surfaces that interact with other working surfaces and thus form working surface pairs (WSP). The effective structure can be illustrated with the help of principle sketches (see figure 3).

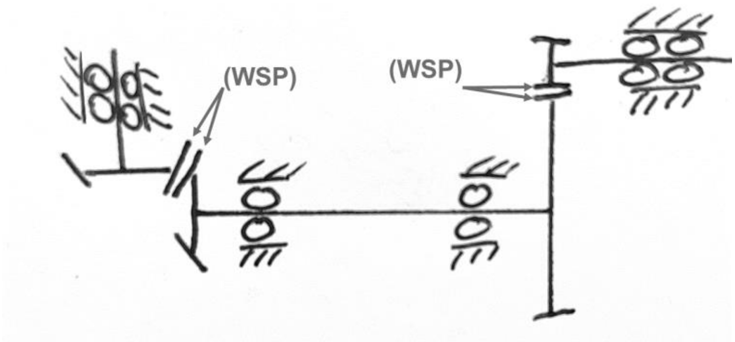

Figure 3. Principle sketch of a two-stage gearbox (WSP)

The effective structure and the associated effective principles cannot be thought of purely on the physical principle level, but presuppose at least implicitly a relation to the embodiment (Matthiesen, 2021).

2.2.2. References in solution concept development

References and variations have to be considered for the development of technical systems on different levels of abstraction and different system layers. References themselves are available at different levels of abstraction and maturity levels (Pfaff *et al.*, 2021). Variations can be understood as patterns of activities of product engineering and appear in different stages of the development process (Albers et al., 2019b). As industry case studies show (eg. Albers *et al*., 2016; Richter *et al*., 2019), references play a major role in concept development. As described in the introduction, there is not yet a detailed study on the use of references in the development of solution concepts.

3. Aim of research and research approach

3.1. Aim of research

As the state of research shows, new products and systems and their solution concepts are developed based on references. Furthermore, the introduction shows that the use of references has an impact on the representation of solution concepts. Therefore, it is necessary to investigate what impact the use of references in the development of solution concepts has on partial solutions, the evaluation, and the representation of solution concepts, as well as what problems developers face when developing solution concepts based on references. In this contribution, it is investigated in the 2019/20 and 2020/21 MSuP student cohort how the availability of references and the methodical support to systematically use these references affected the creation of solution concepts. Furthermore, it is investigated whether the use of references influenced system understanding and evaluation. It is also investigated what challenges and

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potentials the developers encounter when using references to develop solution concepts. This leads to the following two research questions, which are the subject of the present work:

- RQ1: What are the impacts of using references to develop solution concepts in the LiveLab MSuP?
- RQ2: What are the challenges in creating solution concepts using references in the LiveLab MSuP?

3.2. Research Approach

The Live-Lab Mechatronic Systems and Products (MSuP) of the IPEK - Institute for Product Development Karlsruhe at the Karlsruhe Institute of Technology (KIT), with around 100 engineering students per cohort, is used as a research environment to answer these questions. In the Live-Lab MSuP, each of seven teams develops a cooperating real-complex system in two groups distributed over different locations. At the end of the course, this system is evaluated with a score in a simulated market launch according to predefined criteria regarding performance. The MSuP research environment combines real development processes with the transparency of a teaching event, which is repeated annually with minor adjustments to the task and boundary conditions. This event mode makes it possible to provide potential references from previous years, which are made available to the developers to form a reference system by independently identifying suitable reference system elements (RSE).

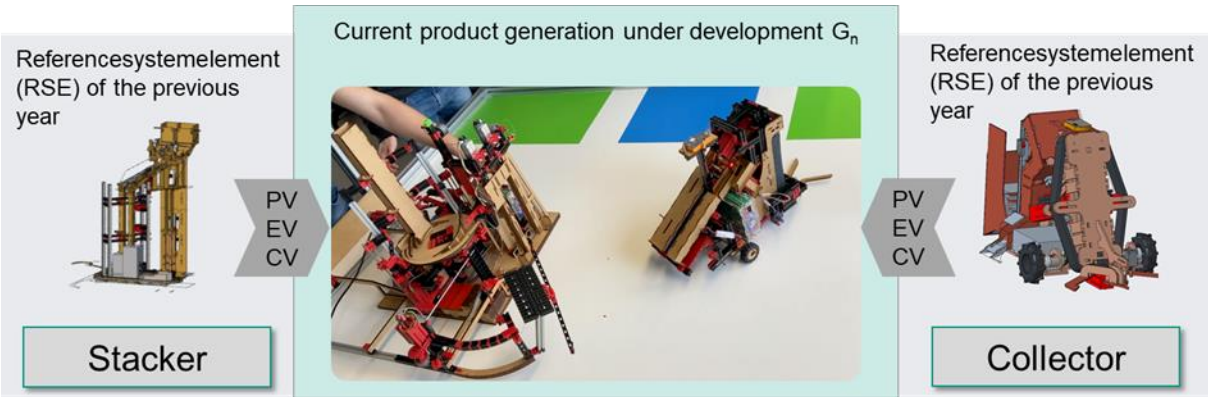

Figure 4. The system in MSuP consists of two subsystems: a moving system, which collects cubes on a board (collector), and a standing system, which stacks the cubes into towers (stacker).

The use of references was initially introduced in MSuP in the 2018/19 student cohort. Selected potential reference products were provided but the developers stated that the number of references was not sufficient to estimate and use them in a targeted manner (Albers et al., 2018b). To address this finding, the scope of references was significantly increased and comprehensive references in the form of project documentation from the previous two years were made available in the 2019/20 and 2020/21 cohorts. The 2019/20 cohort developed based on a few references (200MB data), whereas the 2020/21 cohort had access to all available references from the previous two years (50GB data) and had to identify appropriate reference system elements on their own. These boundary conditions lead to more extensive use of references in the 2020/21 cohort in all of the student groups.

To make the effects of the use of references in the representation and evaluation of solution concepts describable (RQ1), the milestone documentation of the cohorts was examined. Based on criteria derived from the state of the art on solution concepts (see section 2.2), it can be compared objectively to what extent the solution concepts cover certain views: The system view, the functional view, the physical view and the embodiment view. Further criteria are evaluated which indicate the use of references in the development of solution concepts (see Table 1).

An evaluation of the concepts about the requirements defined in the task could not be carried out objectively based on the concept documentation. How well the final products based on the concepts meet the requirements was measured in the final events. Unfortunately, problems arose during the

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recording of the final event of the 2020/21 cohort, which was carried out under COVID conditions and hindered an evaluation of the data about the degree of fulfilment of the requirements.
An evaluation of the provision of comprehensive references (RQ2) was carried out in parallel using an online survey in the 2020/21 cohort as well as individual interviews with the developers.

4. Results

In the following chapter, the solution concept representations in the milestone presentations of the 2019/20 and 2020/21 cohorts are compared according to the criteria defined. This is followed by the results of a survey among the 2020/21 cohort on the impact of the use of references in the creation of solution concepts. Finally, various challenges in dealing with references for solution concept creation, which the developers themselves named in the online survey and the individual interviews and which were confirmed by the organizers of the event, are summarized.

4.1. Use of references and criteria for comparison of cohorts

For the evaluation of the concepts, we determined criteria based on the current state of research, which characterize a concept, and criteria which indicate the use of references in the course. The percentage in Table 1 indicates the proportion of teams whose concepts fulfilled the criteria.

Table 1. Share of seven teams per cohort that meet the respective criteria. 19/20 few referemces 2020/21 all available references from the previous two years

Evaluation criteria	2019/20	2020/21
System view		
System structure visible	57%	86% ↗
Hierarchical - subdivision into subsystems	29%	29% →
Functional - functions assigned to systems	71%	86% ↗
Functional view		
Functions named	29%	71% ↗
Functional structure recognizable (main/secondary/sub-functions)	0%	29% ↗
Critical functions indicated	14%	86% ↗
Physical view		
Effective principles for the individual functions	86%	100% ↗
Effective structure (interrelationship of effective principles)	86%	86% →
Principle sketches provided	100%	86% ↘
Embodiment view		
Photos of references with embodiment information	29%	71% ↗
CAD models	57%	86% ↗
Indicators for the use of references		
Explicit documentation of references	29%	86% ↗
Problems identified based on references	0%	86% ↗
Variation types assigned (CV, EV, PV)	0%	71% ↗
Shares of variations determined	0%	71% ↗
Impact on risk, benefit, effort	71%	100% ↗
Traceability of Reference System Elements (Origin of the RSE)	29%	86% ↗

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The comparison showed that functions were named explicitly in more of the 2020/21 solution concepts. Based on the naming of functions the system had to fulfil, the function view was more pronounced compared to the previous year.

The system view experienced a less pronounced change. The system structure was presented in more cases in 2020/21, the subdivision into subsystems as well as the assignment of functions to systems took place in a balanced manner in both groups.

Comparing the physical and embodiment view, we observed that the ratio of concept representations using principle sketches, photos and CAD models had changed. In the previous year, 86% of the illustrations are assigned to principle sketches and only 14% are distributed between photos of systems and illustrations of CAD models. In the year with more references, 45% of the illustrations are principle sketches and 19% of the illustrations showed real systems with embodiment information. 36% of the illustrations in the year under review showed CAD models. This represented a shift towards more embodiment information in solution concepts in the 2020/21 cohort.

The indicators for the use of references indicate a clear change towards a more extensive use in the 2020/21 cohort. Indicators for PGE activities in concept development were the indication of variation types and proportion of the respective variation type as well as explicitly documented RSE. The use of references in the solution concepts is shown exemplarily in figure 5: On the left side is an example of the 2019/20 cohort with no explicitly documented RSE and on the right side an example of the 2020/21 cohort with significantly more documented RSE. The illustration on the right also includes the initial assessment of risk, benefit and development effort of the subsystems based on the references considered. Furthermore, the proportion of CV, EV and PV were indicated for the generation under development.

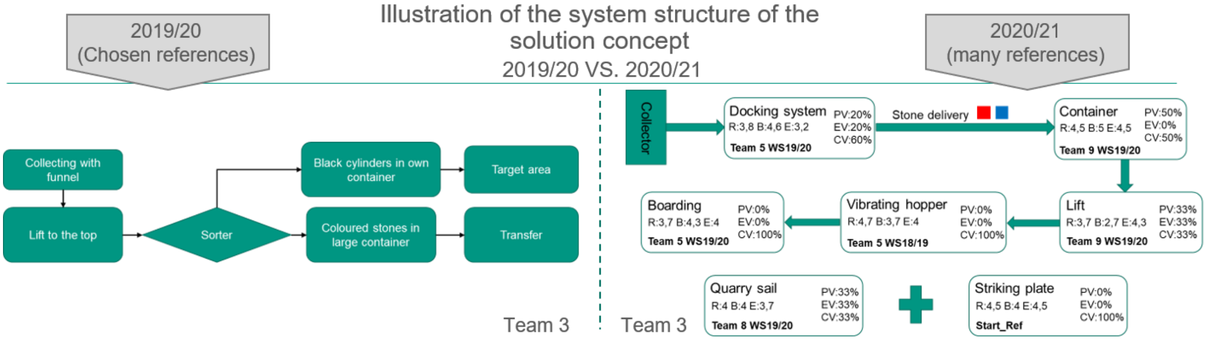

Figure 5. Excerpts from the solution concepts (left) 2019/20 with few references and (right) 2020/21 with many references. The presentation of the solution concept elaborated with many references contains more information about the subsystems.

The illustration and relation to references offered the possibility of a better assessment in the evaluation and selection of suitable solution concepts in an early phase since the elements from the reference system have already been validated by the original developers and successfully used.

4.2. Impact of references on the evaluation of solution concepts

The evaluation of the impact of the use of references assessed whether the analysis of the RSE helped to build an understanding of the system to be developed. By analyzing the references, knowledge about the required functions, structures and dependencies of the functions could be gained. The developers indicated, as shown in the first box in figure 6, that the analysis of the RSE helped them to achieve a better understanding of the system under development. Individual statements also confirmed this support in the online surveys. Once a basic understanding of the system was achieved, the risk, benefit and effort for developing the subsystems could be assessed. The developers considered various solution concepts for the realization of a function. Through numerous references, additional information for the selection of solution concepts could be gained. As part of the evaluation, the developers were asked whether considering the RSE helped them to assess the risk, benefit and effort of their solution concepts (figure 6, three boxes on the right). According to the developers, risk and benefit could be better assessed

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based on references, than the effort required for the development. Not only did the assessment of the effort tend to be rated worse, but the spread in the answers was also much bigger.

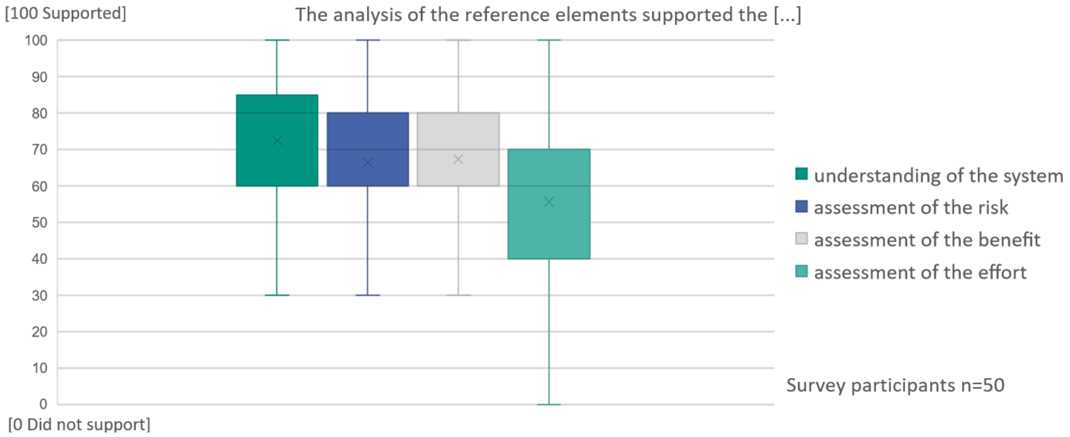

Figure 6. Result of the survey regarding the change in the understanding of the system and the assessment of risk, benefit and effort through the analysis of reference system-elements.

The assessment of risk, benefit and effort by analyzing the reference system elements enabled the identification and prioritization of critical functions based on experience (Bender and Gericke, 2021). The teams independently analyzed the references provided and recognized patterns in the functional failures of the systems of previous years. Figure 7 shows the analysis result of a team in the 2020/21 cohort. According to this, over 50% of the functional failures were due to two main functions.

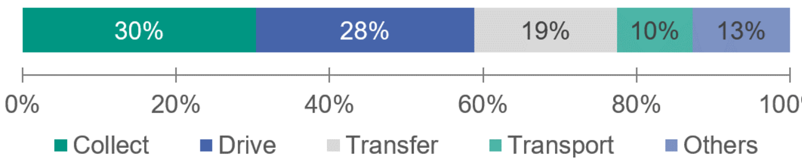

Figure 7. Function failures in qualifying and competition for all Teams 2018/19&2019/20 analysed by a Team of developers in 2020/21

4.3. Challenges in developing solution concepts using references

According to the developers, the advantages, such as concepts with more design information and increased system understanding were also accompanied by challenges when developing based on references. Three key challenges in reference-based solution concept development could be identified through the survey and the interviews.

The developers stated that they felt restricted in their creativity by considering RSE. This became apparent, for example, in the form of a statement by a developer in the online survey:

> *"However, [by looking at the references] my creativity was also severely restricted." (translated)*

The developers outlined an area of conflict between creativity and the use of references. The extent to which the consideration of references limits creativity or can promote a cognitive bias still needs to be investigated in more detail. References can also promote creativity, as shown by the InnoBandit creativity method (Heimicke et al., 2018). Many developers preferred to realize their own ideas; adapting someone else's idea and identifying with an already existing solution repelled many developers. For example, one team openly communicated that they had consciously taken a greater risk than they would have had to take by using another solution based on a reference. One development team formulated this in the context of a reflection event:

> *"[We] always have been aware that new developments like this carry a high risk compared to systems that have already been tried and tested." (translated)*

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The reuse of already validated subsystems is known to the developers as a safer option but is sacrificed in favour of the realisation of one's own potential as the highest human need (see Endriss, 2021).
Building on the findings from Albers et al. (2018b), **the right set of available references** is also a challenge. The teams were able to assess risk, benefit and effort for the development task with the help of already validated subsystems, which was not possible with selected CAD models and test videos alone (Albers et al., 2018b). The developers' wish for more references was addressed in the context of this work. The number of references was rated by the developers as follows: The smaller amount of references was rated on a scale from [0 too few] to [100 too many] with an average value of 37, the extended amount with a 51. The ideal value is 50. The number of references provided was therefore more suitable for the development of concepts based on references than before. The finding shows that a minimum number of references must be available to be able to weigh and evaluate the reference system elements. This is a challenge especially for external reference system elements, as they are often not freely accessible.

5. Discussion and conclusion

In summary, the following findings can be drawn with the help of the criteria based comparison of the solution concepts in the 2019/20 and 2020/21 MSuP cohorts (Section 4.1) and the survey among the developers (Section 4.2 and 4.3). The data and experience reports originate from a live-lab study with students and can therefore not be directly transferred to practice.
The 2020/21 cohort was provided with a significantly higher number of references than the 2019/20 cohort. The criteria for the use of the references indicate clearly that in terms of the model of PGE, more references were analysed, evaluated and finally used in the 2020/21 cohort. The small number of references provided in 2019/20 is not sufficient for developers (Albers *et al.*, 2018b), so the amount of references was increased and finally evaluated more appropriately by developers.
The functional view was more detailed in the solution concepts of the 2020/21 cohort which used more references. In particular, experience-based critical functions were obtained based on the already validated subsystems from previous years which served as references. By considering several references, the awareness of the required and critical functions of the overall system was increased.
According to the developers, the analysis of the extensive references helped to increase the understanding of the system. The analysis supported the evaluation of references regarding their suitability for integration into the generation under development.
The system view in the concepts showed no significant changes between the cohorts. The system structure was marginally improved, a more detailed subdivision of the overall system into further subsystems through the use of references could not be determined.
The embodiment view of the solution concepts developed with extensive references showed a higher share of embidoment information. This was reflected in the high number of teams in the cohort that used CAD models and photos to represent their solution concepts for the subsystems. This was also shown by the ratio of principle sketches to photos of systems and to illustrations of CAD models in the respective cohorts. The ratio of illustrations in the years changed as follows: Share of principle sketches from 86% to 45%, share of photos of systems from 3% to 29% and the share of illustrations of CAD models from 11% to 36%.
We observed that in the solution concepts the degree of functions that have already been transferred into embodiment and validated in previous generations increased.
We suggest that the development of solution concepts using references increases the level of embodiment information, a higher amount of already validated subsystems and a more detailed and critical functional understanding. This research hypothesis needs to be tested in further research.
The advantages in developing solution concepts using references were offset by the following challenges, according to the participating developers.

- The tension between creativity and the use of references
- Adaptation of other people's ideas versus realization of own ideas
- The right amount of available references

These challenges call for a need for methodological support, which needs to be addressed in further work to improve the adaptation of references in the development of solution concepts.

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6. Outlook

It should also be investigated which aspects of development based on references influence the creativity of the developers. Further measures to promote creativity in the use of references in development can be developed in the form of methodological support. Further research activities should continue to investigate the influence of the number of available references on the development, can too many references be available? Is there a minimum number of references to be able to evaluate solution concepts against each other?

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