MODELLING TECHNICAL SYSTEMS IN THE EARLY PHASE: PROPOSING A FORMAL DEFINITION FOR THE SYSTEM CONCEPT

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ABSTRACT

The task of developing "concepts" is common in all fields of engineering, especially in the early phases of product development. However, an in-depth literature analysis showed that authors - often depending on different contexts in design research, education, and industry - define the term "concept" in differing ways. The aspect of reference-based development is rarely addressed in existing definitions. This indicates that there is a need for an updated and concise concept definition. In this paper, the authors propose a new definition of the term "system concept" within the context of SGE - System Generation Engineering that incorporates the findings from the literature analysis. The definition was reflected on in two case-studies. The first one contained the system concept for automotive display and operating systems, the second one the system concept for a kinesthetic-haptic VR interface. The proposed definition contains the relevant characteristics identified from the literature review and supports both current activity-based process models and reference-based development, as practical application has shown.

Keywords: Design methods, Design management, Product modelling / models, Product architecture

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1 INTRODUCTION

In industrial practice and design research literature, the early phases of a product development process are often labelled "conceptualization" or "concept development" (Ponn and Lindemann, 2011). Similarly, design results of the early phases are often referred to as "concept". Our comprehensive literature review shows that, depending on different contexts in engineering research, education, and industry, authors tend to define and use the term "concept" in differing and sometimes contradictory ways (see Table 1.). A survey among concept developers (n=9) conducted at a German OEM in the course of this paper shows there is a need to clarify which partial models are or should be part of a "concept". One area is to understand and support the use of references in the development process (Albers et al., 2019). A study in a student engineering project showed that through using references for the development of concepts, the level of embodiment information was increased, and a higher amount of already validated subsystems and a more detailed and critical functional understanding was achieved. (Schlegel et al., 2022). Existing definitions of the term concept do not yet comprehensively address the aspect of incorporating references. The purpose of this study is a more updated and concise definition regarding the term "concept" considering the mentioned use of references when developing a concept.

2 STATE OF RESEARCH

2.1 Model of SGE - System Generation Engineering

Design methods are often “only suitable for new developments” of products, despite the percentage of actual new developments in modern-day engineering being less than 10% (Kirchner, 2020, p. 8). Innovation success with advanced, complex technical systems can only be achieved economically and with manageable risk by using existing solutions as references, coming from predecessors, competitors, and even industry-external products or research results. The model of SGE – System Generation Engineering describes these relationships. The model is based on two hypotheses (Albers et al., 2015, 2019; Albers and Rapp, 2022): firstly, every development is based on a reference system. The reference system for the development of a new system generation is composed of elements of already existing or planned socio-technical systems (reference system elements, RSE) and represents the basis and starting point of the new product generation (Albers et al., 2019). Secondly, a new system generation is developed based on the reference system through a combination of carryover, attribute and principle variation (Albers et al., 2015, 2020):

Carryover variation (CV) means a RSE is transferred to the new system generation, only by adapting interfaces. The RSE is assumed to be a black box and is not changed. **Attribute variation (AV)** means the RSE retains the links to other elements. The solution principle of the subsystem in the new system generation therefore remains unchanged compared to the reference. Only the attributes of the reference are changed. **Principle variation (PV)** means RSE are added or removed, and links between elements can be added or removed. The solution principle changes compared to the reference.

Case studies show that the success of a product development project is strongly determined by decisions made in the "early phase" (Cooper and Kleinschmidt, 1993). Albers, Rapp et al. (2017, p. 4) state that the early phase "addresses the time range between the trigger for or initiation of an engineering project to the evaluation of a product specification. This specification includes i.a. information concerning the applied technology and subsystems as well as their share of carryover and new development shares. The specification allows a valid evaluation of the planned product regarding relevant parameters such as manufacturability, necessary resources and the technical and economic risk." The early phase can be characterised by features such as uncertainty, use of resources and structuring (Verworn, 2005). Systematically using references can reduce development risk and save resources (Albers et al., 2017).

2.2 The term "concept" in product development

In product development, the term "concept" usually used to refer to the technical "solution concept" (Ponn and Lindemann, 2011) that is developed specifically to propose a solution to a given technical problem. Solutions are synthesized and modelled at different levels of abstraction in the product development process. Ehrlenspiel and Meerkamm (2017) 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). Solution

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concepts are an intermediate result and therefore at least partially solution open. Many process models feature "concept development" as an early phase of the development process. This phase is of great significance, as it is "where the most important decisions are taken." (Cross, 2008, p. 32) In the C-K design theory, Hatchuel and Weil (2003) model the knowledge of developers in the "Knowledge-Space" (K-Space) in which all possible elements of knowledge can be stored. Individual knowledge elements have a logical status, i.e., they are either "true" - which means validated and verified or assured - or "false". Elements whose logical status cannot be clearly defined are understood as concepts in "concept space" (C-space). The result of our literature review indicates that authors differ in terms of relevant activities in concept development and elements of a concept (c.f. section 4). Accordingly, further research is needed to consolidate a common understanding of the term in the intersections, including latest observations on the understanding of reference-based concept development in the research field of SGE.

3 RESEARCH DESIGN

Towards the common understanding of the term "concept", this contribution is built upon three research questions:

- *RQ1: Which definitions of the term are currently in use and which differences and commonalities do they share?*
- *RQ2: Can a unified definition of the term "concept" that reconciles the aspect of reference-based concept development with the established shared understanding of the term be introduced?*
- *RQ3: To what extent can the updated definition reflect observable phenomena in real development processes?*

RQ1 was answered through a literature analysis in both German and English language. Google Scholar, Scopus, and the literature database of the DESIGN-Community were used to identify literature which covered product development processes as a whole or concept development specifically. A total of 34 thematically matching publications were selected using the definition of the term "concept", characteristic elements of concept/concept development as well as similarities and differences to other publications as guiding key factors. Table 1 lists all 34 analysed publications ranked in descending order regarding their relevance on a scale of 1-5. The results of the analysis are presented in section 4 along nine characteristics. Based on these findings, the definition of the "system concept" is proposed in section 5 to answer RQ2 and applied in two case studies in section 6 to answer RQ3.

4 RESULTS OF THE LITERATURE ANALYSIS

In the literature analysis, nine different characteristics (C.1-9) for concepts were identified (c.f. Table 1). The following paragraphs give an overview of the characteristics and summarise the key findings that lead to the proposal for a unified understanding of the term concept in Section 5.

C.1 –Sequential (1A) and activity-based models (1B) of the product development process: Concept development is frequently described as a phase of the product development process. Publications from 1993 - 2019 often refer to the 1993 version of VDI 2221 or adjacent standards. A major advancement of the newer version is the shift from a sequential to activity-based process model. The activity-based approaches for modelling the product development process featured in the 2019 version are more compatible to modern-day engineering work.

C.2 – Concept development based on requirements: A common trait of the underlying development process models is that at least one phase (e.g., "task clarification" (Pahl et al., 2007) and/or multiple activities precede the development of concepts. These first steps are where the requirements are (initially) determined and documented, which are to be met by the product or system in development.

C.3 – Parallel development of concepts: 80% of the examined publications state that ideally, concept development should not be limited to just one concept being developed from start to finish. Instead, multiple technical solution concepts for the same problem are to be developed in parallel.
Some publications recommend developing concepts for different sub-systems individually and later combining them to form a conceptual solution for the entire system (Ponn and Lindemann, 2011).

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Table 1. Nine characteristics are considered important for concept development by currently available scientific work - none covers all nine characteristics

Characteristic (C.) / Analysed Work	C. 1A	C. 1B	C. 2	C. 3	C. 4	C. 5	C. 6	C. 7	C. 8	C. 9
(VDI 2221 (2019) - Part 1 2019)		x	x	x	x	x		x	x	x
(VDI 2206 2021)		x	x			x	x	x	x	x
(Bender & Gericke 2021)		x	x	x	x					
(Felkai & Beiderwieden 2013)	x		x	x	x		x			x
(Ponn & Lindemann 2011)	x		x	x			x			
(Lindemann 2016)	x		x	x	x	x		x		x
(Hales & Gooch 2004)		x	x	x	x	x	x	x		
(VDI 2221 1993)	x		x	x						
(VDI 2206 2004)		x	x	x	x	x	x	x		x
(Gaubinger et al. 2009)	x		x	x	x		x			
(Naefe 2019)	x			x	x		x			x
(Fleischer 2019)	x		x	x						
(Vajna 2014)	x		x	x	x					
(Kirchner 2020)		x	x	x	x					x
(Cross 2008)	x		x	x	x	x	x			x
(Schäppi et al. 2005)	x		x	x	x	x	x		x	
(Pahl et al. 2007)	x		x	x	x	x	x	x		
(Hacker et al. 2015)		x	x	x	x	x	x			
(Ernstberger 2013)	x		x							
(Tecklenburg 2016)	x		x						x	x
(Khare et al. 2018)	x		x	x						
(Hoffmann 2018)	x		x	x			x			
(Sendler 2009)		x	x	x		x	x			x
(Rodgers et al. 2000)	x					x	x			
(Tovey et al. 2003)	x					x	x			
(Chen et al. 2005)	x		x	x						
(Elverum & Welo 2014)	x		x	x		x	x		x	
(Leveson 2018)	x		x					x		
(Will 1991)	x		x	x				**X**		
(Schmidt 1997)		x	x	x	x		x		x	
(May 2020)		x	x	x		x	x	x		
(Huth & Vietor 2020)		x								
(Neugebauer et al. 2005)		x					x			
(Rodgers et al. 2001)	x			x		x				

Legend
x Characteristic has been elaborated on in the publication

C. 7 Calculations and simulations in concept development: Will (1991) found out that process efficiency can be increased since calculations & simulations can shorten necessary developing and testing time.

C.4 – Criteria for concept selection: Selecting a concept from alternatives is ideally achieved using criteria. It is highly recommended to determine and document the criteria to keep the decision-making process transparent and repeatable. Common criteria in engineering include the degree to which a concept fulfils the known requirements, technological or economic advantages and disadvantages and the conformity to legal restrictions and standards. (Cross, 2008, p. 151)

C.5 – Concept presentation and documentation: 15 publications state which partial models or should be part of a "concept". The bandwidth varies from the "principal solution" (VDI 2221, 1993) per se to the architecture of a product (Bender and Gericke, 2021, p. 233). Another aspect is the situation-adequate presentation of a concept to produce a desired effect (Elverum and Welo, 2014), e.g., convincing potential investors. Depending on the purpose of a concept presentation, there are many possibilities to choose from, the most popular of which include sketches and (usually low detail) drawings, slideshow presentations, CAD sketch models (which may include black boxes instead of fully modelled components) or the construction of early "concept prototypes" (Elverum and Welo, 2014).

C.6 – Degree of maturity of a concept: The detailed technical design of a product is not part of concept development. This is subject to subsequent phases (e.g., "design", "elaboration" (VDI 2221, 1993) or "embodiment design" and "detail design" (Pahl et al., 2007)). To differentiate between "concept" and "design", the term "Technical Degree of Maturity" (Albers et al., 2019) ["Reifegrad" (Bender and Gericke, 2021; Albers et al., 2019; Lindemann, 2016; Kirchner, 2020)] is frequently used, referring to the level of detail at which technical solutions are presented. For a concept, the degree of maturity is

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expected to be comparably low. Complete technical drawings featuring manufacturing-related information and detailed CAD models therefore classify as "designs". (Felkai and Beiderwieden, 2013)

C.7 – Calculations and simulations in concept development: Calculations and simulations can effectively shorten the necessary time for developing and testing products and thus increase the efficiency of development processes (Will, 1991). Early calculations and simulations can yield surprisingly accurate cost predictions (Hales and Gooch, 2004, p. 127) or safety assessments (Leveson, 2018), which is why some authors recommend frontloading them.

C.8 – Early validation and prototyping: Manufacturing and using prototypes in concept development is a practice which originates from the automotive industry (Tecklenburg, 2016; Elverum and Welo, 2014). It has since successfully been implemented in other branches of engineering and is rising in popularity as of late, especially because of increased frontloading and parallelization of activities throughout the product development process.

C.9 – Use of references in concept development: Schlegel et al. (2022) show the implication of references for a system's maturity in the early phase. However, less than 30% of the publications analysed consider the use of references at all. Some authors suggest skipping partial steps of the product development process if results are determined using references (Naefe, 2019, p. 53) and (Kirchner, 2020, p. 8)). None of the publications include a proper methodology for developing concepts using references.
The variation type used on a RSE influences the development activities to be carried out (Albers and Moeser, 2016): specifying a technical solution concept can be almost entirely skipped applying CV or AV, as the principal solution for realizing the desired functions is directly taken from the RSE. Only when applying PV on a (sub-) system, it is necessary to develop a technical solution concept, as this entails a change of the solution principle itself and the search for alternatives.
None of the analysed works can currently depict all nine characteristics. In particular, the reference-based development of concepts and concept models is only touched upon in 10 of the 34 publications, and in these only very superficially. This conclusion indicates the extent of the existing research gap.

5 PROPOSING THE SYSTEM CONCEPT AS THE CONCLUSION OF THE EARLY PHASE

Based on the previously outlined research gap, the authors propose a new definition of the term, which, in addition to the previous findings, also considers new research insights on reference-based product development from the model of the SGE - System Generation Engineering (see Figure 1).

> A **system concept** in the model of SGE - System Generation Engineering is a *model of a technical system* that defines the *objectives and requirements* for a system *derived from the product profile,* as well as the system architecture and the *associated reference system elements* and *variation shares*, considering the boundary conditions, and makes them accessible for *validation*.

Figure 1. Proposed new definition for the term system concept in the model of SGE – System Generation Engineering

In this definition, we adopt the key findings from the identified literature, especially C.2 C.6, C.8 and C.9. The "system architecture" includes solutions for subsystems, possibly at different degrees of maturity ranging from principle solutions to detailed designs. Customer and user needs form the basis for the synthesis and modelling of a system concept. Based on the specified objectives and requirements, the system architecture is defined, determining which subsystems are involved in the technical realization and how they interact with each other to fulfil the requirements. According to the basic principles of the model of SGE, this specification always takes place based on reference system elements (RSE). These RSE have to be identified and the intended type of variation has to be specified for each RSE-subsystem relation. The generated objects which model and describe the system concept (e.g., sketches, MBSE-models, graphical models, Matlab models, etc.) can be validated. This process is highly creative and iterative between synthesis and analysis. The specified system concept and the

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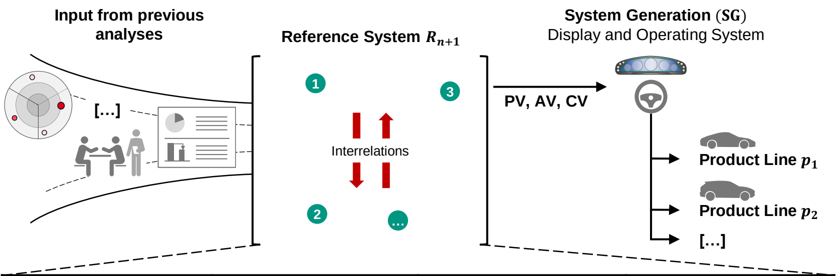
developed objects to describe it form the conclusion of the Early Phase. However, even after concluding the early phase, subsequent changes to the system concept are still possible via change management if necessary.

6 CASE STUDIES

In the following, the insights gained from the definition are reflected using two selected case studies. These also serve as rationales and explanations for the individual elements of the proposed definition.

6.1 Case study 1: Concepts for display & operating systems in automotive industry

New digital technologies lead to growing needs of customers especially regarding the product's in-car user experience and the display and operating systems. We observed that objectives, requirements, and architectural solutions from the reference system are varied based on new or adapted needs, originating from analyses like market trend studies or customer interview studies. The display and operating system is a subsystem of the overall vehicle system. Other subsystems (e.g., the driving system) provide numerous interactive product functions (e.g., the recuperation function of the driving system for energy recovery while driving) with a technical interface to the display and operating system. Accordingly, a display and operating concept is a system concept that describes specific features of the display and operating system of the overall vehicle system. In the early phase, the prioritized use cases in the product profile take on a special role. The case study showed that it is not possible to specify the interaction workflow of all use cases due to the time and effort involved. Consequently, prioritized use cases were defined in the first step based on workshops with the sales department and a qualitative interview study with selected customers and users (see Figure 2). For each use case, RSE were selected based on different analyses. Next, specific demand for variation of these RSE was derived from the analyses in an interdisciplinary development team.



Use Case	Analysis Step	Reference System Elements (RSE)	Demand for Variation for the System Generation
"Coasting" on flat roads  When driving to work in the morning from a residential area onto a flat country road, the function status coasting' is used to drive as efficiently as possible without decelerating throttle torque.	**Trend Analysis:** Evolution towards larger displays in the interior	Infotainment System/ Central Display G_1 Taycan 1	Usable Panel Area: AV of Panel Dimensions
	Interview Study: Qualitative Asessment by Customers and Users	Infotainment System/ Instrument Cluster G_1 Porsche Taycan 2	Displaying Function Level: • CV of Position in Interior (in Driver's permanent visual area) • AV of the Icon showing the current Function Level
		Recuperation System G_2 VW e-Golf 3	Recuperation Statistics: • AV of the Subfunctions for Information • AV of the Interface Design in the menu
	[...]		
[...]			

Figure 2. Documentation of selected use cases in system concept development. Each use case addresses several reference system elements and demand for variation for the SG

These use cases provide the basic structure for deriving (product) objectives and requirements as well as project constraints to be fulfilled by the system generation. System objectives and requirements were decomposed for the display and operating system and adapted to changing stakeholder needs (resulting from the analyses). Next, the system architecture was designed, which is represented by the mutual alignment of the user interfaces in the vehicle interior as well as their inherent logic for

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information input and output. Based on the defined objectives, requirements, and boundary conditions as well as the specified system architecture, the system concept for the display and operating system was further concretized. For each of the prioritised use cases, the interaction flow was modelled. This describes the modality of interaction between the user and the user interface and the resulting flow of information. The technical (display and operating) system can be purely haptic, it can be implemented as a software-based graphical user interface (e.g., a touch-sensitive display) or as a mix of both. Afterwards, the system concept for all considered use cases was aggregated into a single document for standardization and specification purposes (see Figure 3). This serves as a technical system model of the early phase in subsequent development steps to ensure consistent model-based development.
Based on the documentation created, a validation configuration was built. A prototypical seating buck was used whose touch-sensitive displays were equipped with a UI simulation containing the UI concept elements. The environmental model was realized by monitors arranged around the vehicle and a hexapod platform, which could physically reproduce both a company-internal circuit and a public highway section.

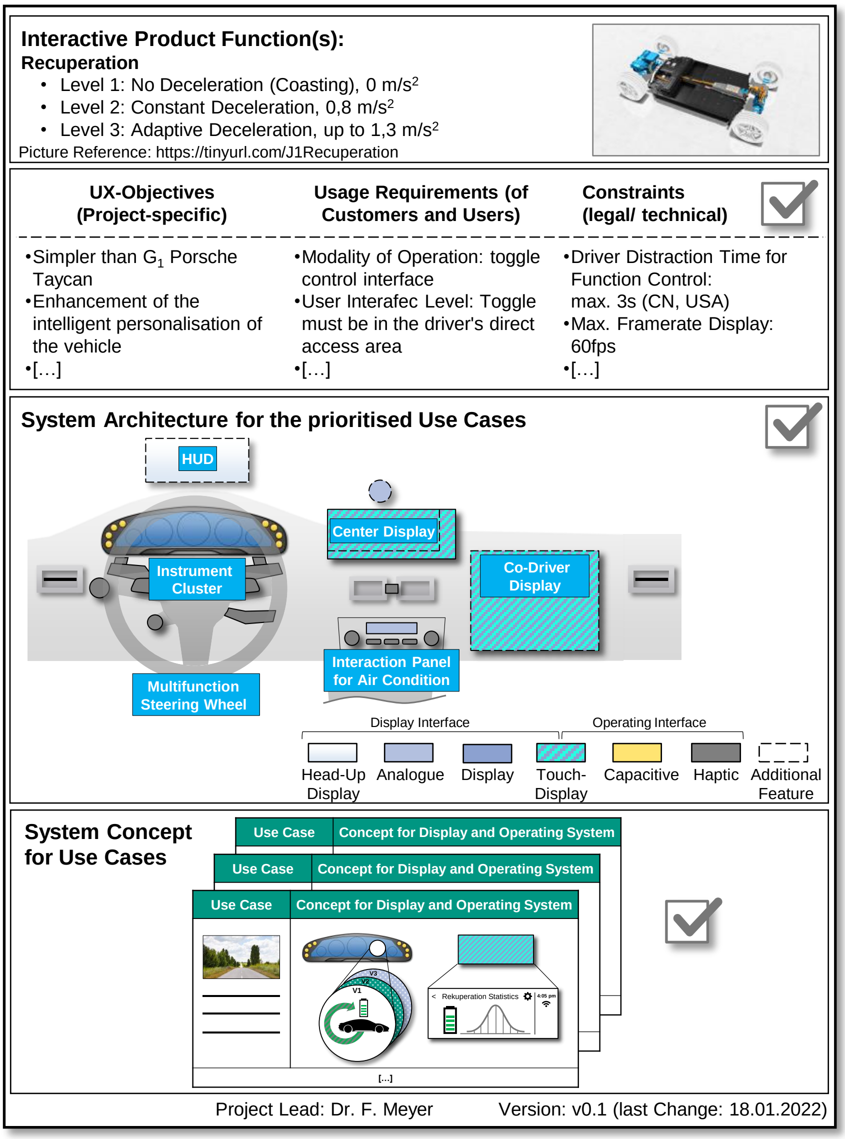

Figure 3. Final documentation of the system concept for the display and operating system containing the system architecture, its objectives, requirements, and constraints as well as the modelled system concept for prioritised use cases of the display and operating system

6.2 Case study 2: Kinaesthetic haptic interface for VR applications

In virtual reality applications today, mainly audio-visual stimuli are generated. To provide the user with physical feedback, special so-called kinaesthetic-haptic interfaces are required to represent forces

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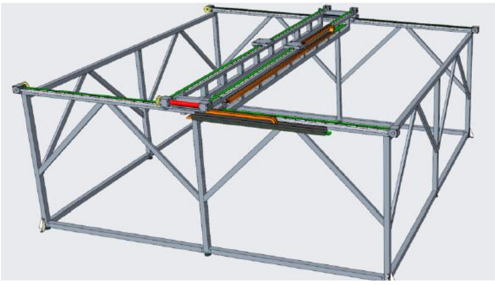
and movements. One of the first haptic interfaces for use in virtual reality is the PHANToM interface, which was developed at MIT in 1994 (Massie, 1994).
One of the world's largest kinaesthetic haptic interfaces - the Holodeck - consists of a two-axis portal crane and a robot arm as a manipulator. The portal crane allows the user to interact with a spacious virtual environment (4mx5m), but due to the only two degrees of freedom of the first generation of manipulators, only a limited number of scenarios could be simulated. The product claim was to develop a new manipulator generation which allows more degrees of freedom to work on current research topics. From this need, the main objectives were derived: six actuated degrees of freedom in all spatial directions, covering the working space of the human arm; high flexibility of the application possibilities; distinct controllability of the system; integrability into the portal crane; use of supply parts or parts manufacturable through turning and milling; safety of the user; adaptability for future use cases; sufficiently high stiffness and strength. In the next step, these aims were specified as requirements and boundary conditions. The basic kinematics of the manipulator (arrangement of the joints and length of the links) were determined using a method developed by Fennel et al. (2021). Figure 4 (Right) shows the basic system structure with joints and links.



	Länge [mm]
Link L2	529
Link L3	668
Link L4	708
Link L5	423
Link L6	0
Link L7	120

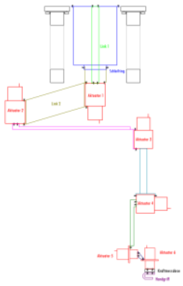


Figure 4. (Left) CAD model of the portal crane
(Middle) A user in the holodeck interacting with the G_1 manipulator
(Right) The kinematic design for the manipulator according to Fennel et al. (2021)

The METUS rhombus (Brökel et al., 2017) was used to model the system architecture through the combination of the functional structure and the system structure. At this project stage, the initial system of objectives, the kinematics, and the architecture were specified. The system concept still was not defined sufficiently as RSE, and variation types were missing to define the technical solutions for the subsystems. As there was little design experience in robotics in the team, an extensive reference system had to be built and analysed for the further synthesis of the system concept. Through the synthesis and analysis of the reference system and its elements, three basic design alternatives could be identified: The exoskeleton construction and the frame construction with aluminium or CFRP support structure (see Figure 5). Two detailed architecture solutions were derived. The exoskeleton design was excluded due to the complex necessary manufacturing process. For the two system concept alternatives, variation types were defined based on the RSE, and initial simple CAD models were created.

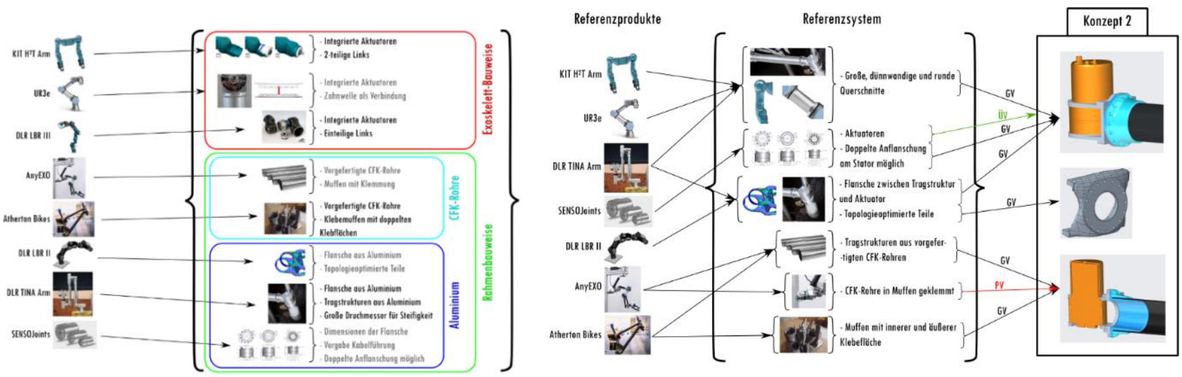


Figure 5. (Left) Different design alternatives
(Right) Frame construction with CFRP support structure

The final architecture solution was selected by means of a utility analysis with criteria derived from the requirements and boundary conditions. This resulted in advantages for alternative two, particularly

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regarding manufacturing costs and weight. The types of variation and reference system elements therefore played a major role in the cost and risk assessment and the planning of further validation activities. However, as there was no RSE with glued sleeves and little know-how in the field of glued connections in the team, it was decided to secure this principle variation through an early validation step before the detailed design. For this purpose, after consultation with the manufacturer of pipes and adhesives, a prototype of an inner and outer sleeve was manufactured, and a carbon pipe was procured. In the test, the glued joint was loaded with over 1500 N transverse force and 1000 Nm tilting moment without showing any damage or deformation. As these values far exceed the permissible loads on the actuators, the solution was considered to provide sufficiently high stiffness and strength.

7 DISCUSSION AND CONCLUSION

Regarding RQ 1, we observed that the individual definitions of the term "concept" vary between authors. Nine characteristics of concepts could be identified in the literature analysis, but none of the analysed publications covers all of them. Especially for validation purposes, references as the basis for concept development activites are an important part of a system concept. Likewise, a continuous link between needs, objectives and requirements and the system architecture is lacking in most definitions. The proposed definition of the system concept answers RQ 2. It supports the reference-based concept work in the early phase of product development. The definition describes decisive aspects starting with setting up the reference system, deriving objectives and requirements, and ending with the synthesis of architecture solutions. The definition was reflected on in two case studies in development practice. to answer RQ 3. In both cases, the objectives, and requirements for the system concept as well as the boundary conditions were derived from the needs and specified iteratively as well as validated using the architecture solutions. In addition, both examples show that the reference system in concept development is initially set up by concept developers and then continuously analysed and expanded. For developing architecture solutions, variation shares were defined for selected reference system elements. Both concept models were used to validate the system concept, followed by the implementation. Hence, both cases have shown a good fit of the proposed definition for concept work in practice. Consequently, the definition is accessible and valid for a wide range of applications, especially in systems engineering. This promotes a future-proof and cross-company understanding of the conceptual term, supporting targeted concept development across teams within and beyond organizations (e.g., with contractors or in a cross-company joint development project).

8 OUTLOOK

The main task is to critically examine the validity of the proposed definition in further case studies and to refine it according to changing demands. Especially the linkage of the system concept with the product profile offers further need for research. It is particularly important to investigate how product descriptions such as fact sheets or comparable documentation interact with (sub-) system concepts in the early phase. In Case 1, a summarizing documentation of the system concept was created as part of the project. In order to take into account the evolution towards model-based systems engineering, it is necessary to integrate these early document-based system models into the tool landscape and make them accessible to the relevant developers as a continuous reference for further subsystem concepts as well as the technical realization of hardware and software subsystems. Based on this understanding, more targeted and demand-oriented methods and tools can be developed to support the reference-based synthesis of system concepts.

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