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Designing an Embodiment - a design methodology perspective

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ABSTRACT: Gradually transforming abstract, conceptual ideas into physical assemblies is seen as one of the key competences of design engineers. Despite the general recognition of the Embodiment Design task as essential phase of every development process, a general methodical support seems either not available or, at least, not influential. Instead, Embodiment Design is often considered an expert task. In this context, our paper offers a discussion of embodiment design from a design methodology perspective. Drawing from a review of relevant literature, we explain why embodiment might be better understood as the representation of the physical artifact rather than a design phase, provide properties and characteristics of good embodiment solution, and give initial guidance for the transition from the creative exploration of concepts to the actual search for satisfactory, or even optimal, embodiments.

KEYWORDS: Design methodology, Design engineering, Mechanical Design, Embodiment design

1. Introduction

Gradually transforming abstract, conceptual ideas into concrete physical assemblies that can be produced economically is generally seen as one of the key competences of design engineers (Pahl and Beitz, 2007; Ulrich and Eppinger, 2016; Andreasen et al., 2015). Despite the importance of this *Embodiment Design* task and its general recognition as an essential step of every physical development process, embodiment practice has been mainly driven by experience and the reuse and/or incremental development of previous solutions (Husung and Weber, 2016; McMahon, 1994). From the authors' perspective, no general, methodical support for the systematic synthesis and exploration of embodiment solutions seems available or, at least, influential. Instead, design methodology, at large, focuses on qualitative design tools and processes that emphasize divergent thinking, stimulating creativity, and avoiding human biases in conceptual, hence earlier, design phases. The underlying reasoning is that a wide-ranging conceptual exploration avoids the unintended fixation on a limited set of ideas (Crilly and Cardoso, 2017) and increases the set of potential design options, hence ultimately increases the likelihood for a positive design outcome (Chakrabarti and Bligh, 1996).

Correspondingly, the general understanding is often that the conceptual design phase is most relevant for defining the overall footprint of the product, as for example discussed by Andreasen et al. (2015). This refers either to production- and lifecycle costs but can also be understood in terms of the realisation of desired product properties, as visualized in Fig. 1. At the same time, it is equally well-accepted that particularly the earliest design phases face a significant lack of product knowledge (Ullman, 2017). This ill-structured nature of development tasks implies that early decisions can only be taken based on a relative comparison among the found design alternatives (Simon, 1996), e.g., implemented in a Pugh-Matrix as a "better than" or "worse than" evaluation compared to a reference design (Pugh, 1990).

With this paper, we would like to offer an additional viewpoint on this general dilemma in design processes, also referred to as a design paradox (Ullman, 2017). While we deeply agree with the importance of a wide-ranging conceptual exploration, we feel that the question of what information is

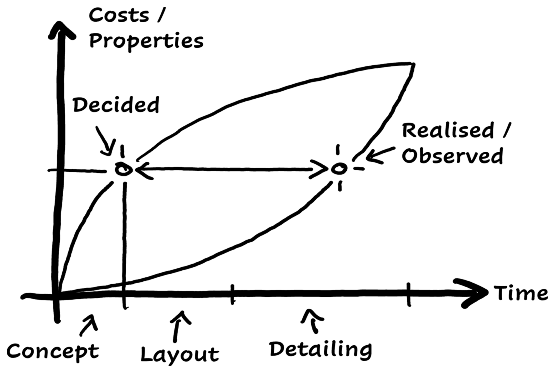

Figure 1. Disposition of cost and properties in early development

available for evaluating and choosing conceptual solutions is too rarely addressed by design literature. An illustrative example is the idea of functional modelling and a first concretisation of functions by means of simple physical principles. Discussed in seminal books as well as by Stone and Wood (1999) or Bohm et al. (2017), just to name few examples, it is, without doubt, one of the best-know and mostly applied approaches in (academic) conceptualisation processes. While the modelling of solution ideas by abstract functions is essential for structuring a design synthesis task, for reducing its complexity, for stimulating creativity, and for avoiding design fixation, we follow Howard and Andreasen (2013) and postulate that the resulting conceptual solutions are largely binary:

> *'A conceptual solution only allows for a high-level decision whether it either has the potential to deliver a particular function or whether it does not!'*

In other words, a conceptual representation does not provide sufficient information to determine how well the function will be fulfilled or how good the actual product will be, nor is that the aim of conceptualisation approaches. Out of our perspective, the main question is consequently not whether conceptual decisions have an important impact (*in most cases they will*)! Instead, the key insight should be the fact that *assessing a concept without its embodiment is inherently problematic!* After all, different cognitive processes are relevant when moving from a creative mapping of ideas to the synthesis of complex assemblies and the consideration of various technical interdependencies, a fact that has been discussed in a design context by Kannengiesser and Gero (2019) (based on Kahneman's dual-system theory) and in general problem-solving research by Öllinger and Goel (2010).
With this paper, we therefore seek to stimulate a discussion about a more systematic transition from conceptual ideas to initial embodiment solutions, and advocate that this step should be considered an essential step in all physical development tasks. For this purpose, and drawing from a review of relevant design literature, we ask the question whether the term *Embodiment* might be better understood as the representation of the physical artifact rather than as a design phase in order to:

- underline the importance of creating an initial, often partial, *Embodiment* solution for structuring the ill-structured nature of every development task, also beyond conceptual design,
- clarify the role of this Embodiment as basis for a more concrete course of action when moving from the creative mapping of ideas towards a more analytical exploration of design solutions.

Accordingly, the remainder of the paper is organised as follows: after a summary of the *Fundamental Background*, incl. typical design processes and available support for the embodiment phase, we offer our understanding of the *Nature of Embodiment*. On this basis, we discuss *Embodiment from a Design Methodology perspective*. Clarifying the notion of *Embodiment functions*, the role of arranging components in an overall product structure, hereinafter referred to as *Embodiment composition*, and the importance of (partial) *View models* for a complex task, the paper provides an overview of relevant reasoning steps when transitioning from abstract product ideas to an initial embodiment.
Lastly, a short word on the origin of this paper. The discussion of the embodiment activity presented in this article started in form of an initial confrontation of two well-known and widely used schools of thought, namely the articulation of the design activity following Pahl and Beitz (2007) and the Domain theory presented by Andreasen et al. (2015). Given long, informal discussions, this confrontation has

been extended towards other design approaches, only some of them included in this article. As we deeply agree with, and also adopt, many of these previously presented thoughts, e.g., the Function/Means tree idea (Hubka and Eder, 1988) or the C/K theory (Hatchuel and Weil, 2009), we are not aiming at a new or alternative methodology. Instead, we hope that our mental framework for these ideas helps structuring the notoriously marginalised complexity of the embodiment task and bridges the current gap between a design perspective and detailed engineering theory. In particular, as it is this gap that we have experienced as main challenge when teaching practitioners or students that come with a more traditional engineering background. In the end, the paper is hence based on our firm belief that *design knowledge and expertise should be a driving factor, also for more detailed engineering task!*

2. Fundamental Background

The following section offers an overview of some fundamental concepts underlying our question of synthesising successful embodiment solutions. Given the abundance of work in the field of design methodology, the paper abstains from a comprehensive literature review. Instead, the main aim is to highlight some, from the authors' point of view, key insights in relation to the embodiment activity. And while we certainly could have chosen more or other sources, we hope that the providedReferences equip readers with limited design background for the subsequent discussion on design freedom and tasks when transitioning from conceptual ideas to the first physical solutions. Readers with extensive methodical background may safely skip this section.

2.1. An overview of the Design Activity

The question of design synthesis, i.e., finding innovative solutions that provide an added value, is at the core of every design process. In general, the design process may be seen as a top-down progression where abstract functional entities are synthesised and gradually concretised into a system that is suitable to fulfil the desired functionality, or more specifically to achieve the desired product properties. Traditionally, this process is described in sequential order from the identification of a relevant problem area and the definition of functional entities, through the choice of suitable physical phenomena, towards the concretisation of suitable working elements, interacting parts, geometrical features, etc. as illustrated in Fig. 2 a) or numerous similar representations in literature, e.g. in Pahl and Beitz (2007); Andreasen et al. (2015); Ehrlenspiel and Meerkamm (2013). Complementing this aspect of gradual concretisation, the corresponding visualisation also includes the idea of divergent and convergent design steps. The underlying reasoning is that the process supports creative exploration of potential conceptual solutions and avoids unintended fixation or biases (*Divergence*), all while controlling the size of this solution set by systematic prioritisation and, once possible, analysis (*Convergence*). These strategies are also summarised in the well-known Double Diamond model (Design Council, 2007) in Fig. 2 b) that, furthermore, underlines the largely ill-structured nature of any design task by the differentiation of *Problem space and Solution space*.

However, and despite various other detailed prescriptive design process models, the question how design synthesis progresses after the initial conceptual design phase is less clearly described in the literature. At the same time, there are some essential aspects that are worth taking into account. Extending the idea of problem decomposition and sequential concretisation, Hubka and Eder (1988) point out that not all relevant functional entities are necessarily know in the beginning of the design progression. In other words, the concretisation of design ideas is a necessary step to structure the ill-defined task, also beyond the problem space highlighted in the Double Diamond model. The corresponding alternating pattern of identifying (sub-) *Functions* and conretising them with specific *Means* is shown by the Functions/Means (F/M) tree representation in Figure 3 a). Furthermore, we understand the Concept & Knowledge (C-K) Theory, which explains the design activity based on the delimitation of *Concept space* and *Knowledge space* as a generalised form of this insight, see Fig. 3 b) and Hatchuel and Weil (2009). In this sense, the formulation and conretisation of a concept (**C**) is an essentially necessary step to gather additional information, and in turn knowledge (**K**), that helps structuring the design task and is fundamental for advancing the design progression.

As basis for our ambition to clarify the nature of the embodiment activity, we, furthermore, put the idea of properties and characteristics at the core of our considerations. With this, we follow different authors who have provided the underlying seminal thoughts, e.g., Weber (2014), Birkhofer and Waldele (2009), or also Andreasen (1976). In general, properties are articulating a product's goodness in the widest sense,

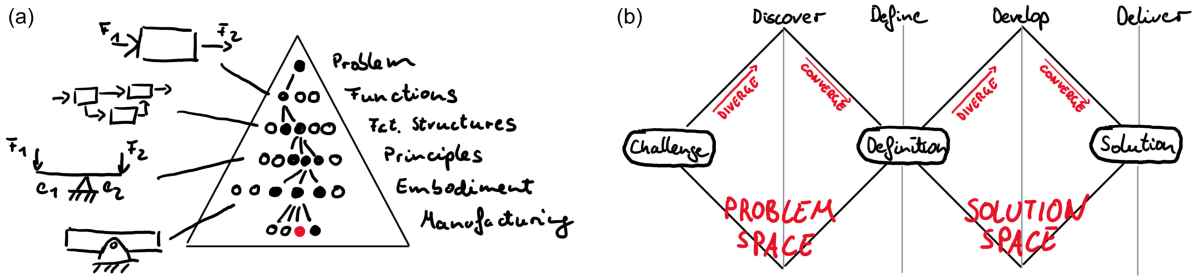

Figure 2. Design activity in a) sequential order, b) as problem and solution space

and they articulate to what degree a product corresponds to the users', buyers', and stakeholders' expectations. Following Andreasen et al. (2015), we define properties as:

> *'Properties are a behavioural class of devices' and activities' attributes, by which a product shows its appearance in the widest sense and creates its relations to the surroundings.'*

Product properties (e.g., product functionality, reliability, or aesthetics, as well as lifecycle-related aspects such as manufacturability, environmental impact, etc.) are consequently resulting from the behaviour of a product in its use context and cannot be directly defined by the design engineer. Instead, they depend on both, the product characteristics that are influenced during development (e.g., structure, shape, dimensions, materials and surfaces) as well as the environment in which the product is placed in. In a design process, the desired properties might for example be given by the customer and need to be fulfilled by the design activity that gradually defines characteristics of the developed solution. Following the same reference as above, we consequently define characteristic as:

> *'Characteristics are a class of structural attributes of products and activities determined by the synthesis of the design.'*

In an attempt to further detail the importance of embodying these product characteristics towards fulfilling specific properties, we refer to Weber's Characteristics-Properties Modelling (CPM) and Property-Driven Development (PDD) (Weber, 2014). The corresponding model in Fig. 4 a) explains how the determination of properties may proceed by formulating a property model showing the relation R between certain characteristics $c_j = 1, \ldots, m$ and the properties $P_i = 1, \ldots, n$. Additionally, this relationship is dependent on the external condition EC, e.g., the conditions in the situation or life phase where the actual property plays a role. When the relation and the satisfactory value of the property is found, a next design step for a second property may be taken.

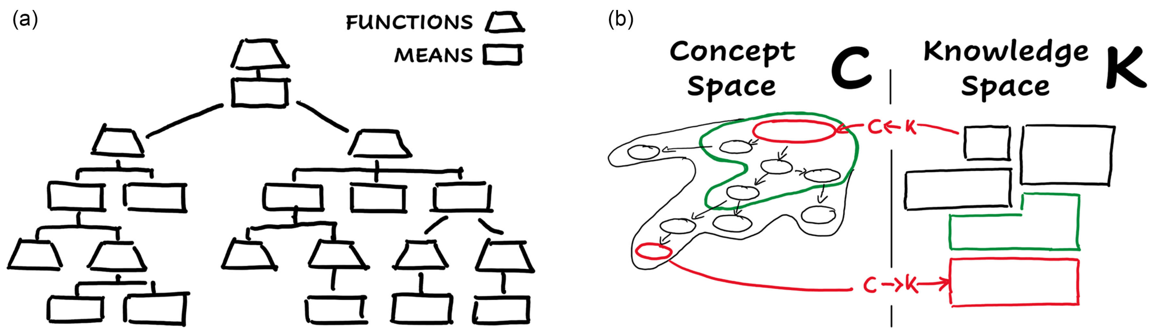

Figure 3. Design Activity based on gradual structuring of the design task based on a) F/M tree and b) differentiation of C-K space

Overall, the design activity is consequently understood as systematically structuring a complex network of dependencies that is growing with the number of functions, hence expected functional properties, and the actual means and characteristics that are gradually defined during the development for fulfilling them. However, concrete support for reasoning about these relevant dependencies is not provided as part of the model! Also in general, we feel that the question of analytically describing and analysing structural dependencies is only superficially covered in many design processes, if it is mentioned at all. A notable exception is the Function-Behaviour-Structure (FBS) framework by Gero and Kannengiesser (2014), see Fig. 4 b). Also referring to follow-up publications (Kannengiesser and Gero, 2019), the framework underlines the character of designing the physical solution as an analytical, corrective loop where requirements *R* are gradually concretised into a statement of Function *F* with an interpretation of the to-be behaviour *Be*. The designer's search for a physical solution may be articulated as search for a structure *S* that shows the actual behaviour *Bs*. The comparison of wanted and now proposed behaviour determines if the solution is satisfactory, or whether a search shall be continued.

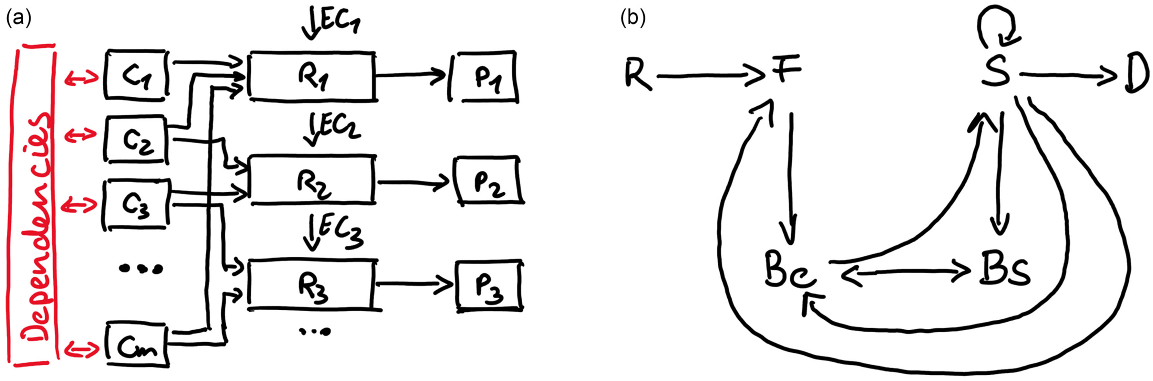

Figure 4. Analytical aspects of the design activity following the a) CPM/PDD and b) FBS framework

2.2. Embodiment methods and tools

While most of the above design approaches include a reference to the embodiment tasks, i.e., to the materialisation of a conceptual solution, they leave an important white spot when it comes to the underlying reasoning. Exemplarily, we therefore quickly summarise three different directions of work in this sparse field; (1) *Design principles & Design guidelines*, (2) *mapping of dependencies in complex systems*, and (3) *cognitive reasoning processes in later stages of design.*

In contrast to the clearly described procedures in conceptual design, traditional design support for the embodiment task comes in form of a long collation of design principles (Pahl and Beitz, 2007; French, 1992), i.e., valuable heuristics extracted from existing "good" or "bad" solutions (Fu et al., 2016). Yet, all heuristics are inherently contextual given that they are extracted from specific existing designs and development tasks. Moreover, the questions of how to balance the different heuristics or how to design toward achieving multiple goals are less well described. As a consequence, the decision, which principle can be applied when, remains largely experience-driven, particularly in light of a growing number of objectives, part interactions, and technical constraints.

In another direction, literature therefore also covers the mapping of this complexity, which has proven value for numerous design task, the most prominent example taking the form of a design structure matrix (DSM). In a reverse engineering manner, a DSM maps interactions between the different system elements with the aim of defining a suitable modular structure, streamlining design processes, etc. (Eppinger and Browning, 2018). With a clear relation to embodiment design, several authors also seek to enhance functional representations with additional information about the underlying physics and constraints when moving towards a physical artifact. Examples are the enhanced F/M tree (Müller et al., 2019) or the dimensional analysis conceptual modeling (DACM) framework (Mokhtarian et al., 2017). Covered early on in (Andreasen, 1976), it seems, however, that the extension of conceptual tools has not yet seen wider application, presumably due to the fact that mapping all dependencies remains too resource-intensive for a broader exploration of solutions.

Lastly, we would therefore also like to highlight the consideration of cognitive processes in design. Predominately focusing on early stage processes (Crilly and Cardoso, 2017), corresponding work has also shown some interesting aspects in relation to the later stages of designing the physical systems. At the same time, existing studies do not show much methodological diversity (Neroni, 2017) as they are too often relying on manual experimentation and case examples of limited complexity (Motte et al., 2004; Snider et al., 2016). As a consequence, available results only interesting initial insights, but do not reflect the approach of design practitioners. They find pragmatic solutions when fitting functional and embodiment compositions together.

3. On the Nature of Embodiment

As shown above, seminal literature usually presents conceptual design as a well-described and generally accepted step-by-step procedure, which addresses the ill-structured nature of the development task by managing its complexity, reducing cognitive biases, and stimulating creativity. Essential aspects are a focus on problem understanding (*Problem vs. Solution space*), a strategy of abstraction and problem decomposition (e.g., *Functional modelling*), and a systematic mapping of possible design directions (*divergence & convergence, morphological analysis*), see also approaches in Fig. 2. In contrast, literature on embodiment design typically comes as a long collation of potentially valuable design heuristics (Pahl and Beitz, 2007; French, 1992) or highlights the opportunistic and pragmatic nature of the task (Bender and Blessing, 2004). It consequently seems widely accepted that embodying functionality into a physical solution is a matter of knowing what decisions to make when, or knowing when a given rule of thumb is useful or when it is not. This also seems to reflect general industry practices.

But why this lack of concern for theory and methods? Fundamentally, it is well-recognised that the realisation of functionality through physical elements is at the core of every design process and requires a '*feasible mapping from abstract product function to product form*' (Kurtoglu and Campbell, 2009). Firstly, this step comes with a drastic increase in complexity given the number of system elements and -interactions, only few of them specified by the concept (Ulrich and Eppinger, 2016). Secondly, we would like to especially underline the aspect of *feasibility* in the above quote. Aligned with our initial working hypothesis on the binary nature of conceptual solutions, the transition from abstract ideas to the arrangement of physical components implies that we are gradually moving towards a more analytical design approach that clearly differs from the creative 'wayfinding' in conceptual design. Instead of simply mapping interesting ideas, the task now includes designing increasingly detailed *characteristics* that fulfil the expected value for (functional) *product properties*, all while complying with an increasingly complex set of technical constraints as also illustrated by the approaches in Fig. 4. In other words:

> *Design gradually moves from a largely unbounded mapping of coarse conceptual ideas towards the actual search for a satisfactory or even optimal solution!*

While we see the above as an uncontested aspect of physical development, we, however, perceive the strict delimitation of the conceptualisation- and the embodiment task, as for example presented in Pahl and Beitz (2007), as quite misleading in this context! We base our reasoning on the following:

> → on the one hand, the ***ill-structured nature of the development task remains*** when moving from abstract idea to arranging physical components! Most development tasks will allow for substantial design freedom related to component design, functionally relevant interfaces, as well as the optimal arrangement of components, and design iterations will often lead to changes in the overall product layout or even a complete conceptual (re)design. Consequently, there will be a growing number of potential design ideas as solutions get increasingly detailed (Liu et al., 2003), which drastically limits our possibility to cover them under one unified (parametric) model (Papalambros and Shea, 2001).
>
> → on the other hand, ***concretisation is critical for structuring this ill-structured nature of the task*** as also suggested by the approaches in Fig. 3. Not only do we see the assessment and comparison of concepts without any form of embodiment as inherently problematic! The metamorphosis from a functionally defined concept to an embodied product structure is, in general, a decisive step for widening and understanding the available problem and solution space. Some required functions might, for example, not be apparent to the designer without a more detailed understanding of the achievable product properties based on an initial embodiment. Others cannot be addressed at all before the materialised structure allows for a first assessment of relevant life-cycle aspects, manufacturability being the prime example.

Accordingly, we understand the task of creating an initial embodiment as a more analytical form of 'wayfinding' and postulate:

‘Embodiment is better understood as the materialised realisation of conceptual ideas rather than as a design phase.’

Our reasoning is that any form of initial Embodiment representation has a balancing role between the creative mapping of ideas and their subsequent analytical maturation, also referred to lateral and vertical transformations in problem solving literature (Öllinger and Goel, 2010). In this spirit, we argue that even initial, partial representations of the embodiment allow for generating new insights and, in turn, a refinement of solutions or new conceptual ideas. This also aligns well with result found by Brun et al. (2016) that design sketches play a decisive role for *‘knowledge preordering’* in the sense of the C/K theory.

What is the challenge with the current treatment of embodiment then? Out of our perspective, the lack of theory and methods, a too often misunderstood delimitation of conceptual and embodiment design, and the consideration of embodiment as a design phase that is necessarily relying on experience pose a significant risk for the overall success of development projects. After all, ‘*ill-structured problems are simply structured by adding information from our background knowledge*’ (Simon, 1973). Be it in conceptual design or related to the embodiment, a lack of information may consequently result in decisions that are subject to biases or individual beliefs and *a development procedure by democracy rather than a suitable analytical approach*. Even worse, these aspects further result in an apparent *disregard of the substantial design freedom* and an increased *tendency for premature design fixation* once the chosen concept is materialised in its initial embodiment, an aspect that has also been highlighted in literature on CAD modelling (Robertson and Radcliffe, 2009).

4. Embodiment - a design methodology perspective

Above, we have given our understanding of the nature of embodiment, including our perception that current approaches are susceptible to biases and premature design fixation. Instead of suggesting yet another method or set of heuristics, we therefore focus on the question of how to structure the transition from abstract function to physical product from a design methodology perspective, i.e., seek a more *‘concrete course of action for the design of technical systems that derives its knowledge from design science, cognitive psychology, and from practical experience in different domains’* (Pahl and Beitz, 2007). Accordingly, we address the issues discussed above by an initial overview of important *Embodiment tasks* and provide a first terminology for *Embodiment Eigen-functions*, the *Embodiment composition*, and the importance of *View Models*.

For our considerations, we choose an extended representation of the F/M tree as mental backbone. Once again, we would, however, like to underline our perspective that, while it should theoretically be possible to describe a given embodiment with all its details in a F/M tree, the underlying functional considerations do not do not automatically lead to an embodiment! Instead, creating an initial embodiment still remains a synthesis step based on experience, engineering knowledge, and reuse of available solution patterns, eventually supported by sophisticated retrieval algorithms in the future.

Our initial overview of relevant embodiment tasks in Fig. 5 is consequently not a guidance to create the initial embodiment, but rather shows its role in structuring reasoning steps where a creative and an analytical design approach are tightly linked. This includes: **(1)** the *prioritisation of key functions* and the specification of expected properties; **(2)** the *synthesis of an embodiment* for the specified functions; **(3)** an *evaluation of the available embodiments* based on functional properties, incl. an initial understanding of

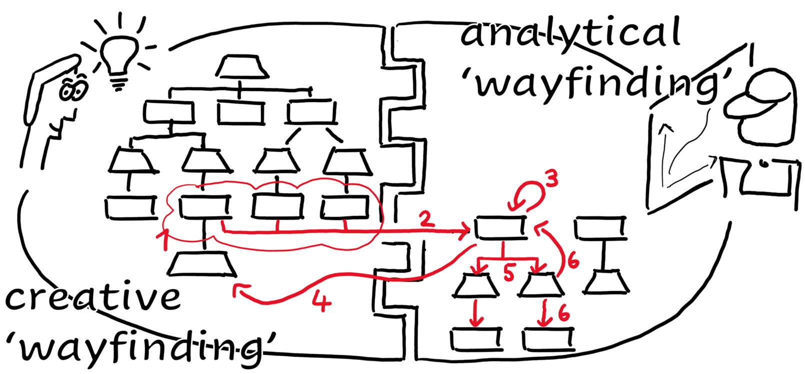

Figure 5. Overview of Embodiment Tasks in an extended F/M tree

missing functions, sensitivity towards specific characteristics, goodness of the solution, etc.; **(4)** the *specification of additionally necessary functions* that are needed for achieving the expected functional properties and will lead to a new loop of conceptual considerations; **(5)** the *identification of relevant Embodiment Eigen-functions* and corresponding properties that are, strictly speaking, not existing before a materialised artifact is available and will, lastly, **(6)** result in a *corrective loop and/or new means* in the analytical domain.

Related to the synthesis of the embodiment (step **(2)** in Fig. 5), we furthermore like to highlight the two different levels of this composition task. First of all, all functional entities, for example presented in a functional structure (Pahl and Beitz, 2007) or an organ structure (Andreasen et al., 2015), need an *internal composition* in the form of bodies as material carriers of physical phenomena and specified interactions between them. As also illustrated in Fig. 2 a), this is in line with most conceptual design literature and supports the systematic identification and combination of potential sub-solutions. However, particularly for mechanical systems it is rarely the case that these sub-elements work independently of each other. Given physical interactions between them and numerous side effects such as wear, heat, and corrosion, as well as the corresponding constraints, a suitable spatial arrangement and alignment for all elements is necessary to satisfy the main functions (e.g., the necessity to fixate a crankshaft, bearings, and cylinder in space) and to ensure relevant life-cycle properties (e.g., manufacturability, robustness, maintainability, sustainability, etc. as presented by de Weck et al. (2011)). In fact, engineering designers will, in most cases, spend more time on anticipating and mitigating the wide array of side effects and life-cycle properties than on the product's main functions! Therefore, we refer to this additional task as *Embodiment composition* and suggest that the created embodiment may be seen as a product in itself, that is with its own *'Eigen-functionalities'* and related properties, to support this analytical 'wayfinding' in Fig. 5. In this sense, the aim of designing an embodiment should consequently not be perceived as an assessment of how well the solution will perform, particularly not early in the design process. Instead, and as laid out in the sections above, we hope that our mental framework induces the designer to use any form of embodiment to gradually systematise and extend the available knowledge base. This includes a better understanding of relevant interactions between functional entities, sensitive influence, limiting constraints, trade-offs, and possible directions of improvement (step **(3)**) as basis for steps **(4-6)** as well as changes of the embodiment layout or even a complete conceptual redesign (not shown in Fig. 5). And we assume that engineering designers, also on a relatively coarse basis, are able to reason about these dependencies, even if it is just in a form of "the further outward components are positioned, the less efficiency this functional working principles might have".

Lastly, we would also like to highlight that all our thoughts above imply that an embodiment is necessarily a partial representation of a product. Initially introduced by Mortensen, we adopt the term *View model* to express that we do not require all available product data, but rather a meaningful subset of information necessary to assess properties and relevant dependencies:

> *An embodiment is a partial-systems view to articulate a certain functional property or the structure of 'eigen-functionalities' and their behavior.*

While this means that we need to operate with more views for obtaining a full understanding of the product, our approach assumes that most designs are based on a clear prioritisation of relevant functions and properties, where usually only small subset of key properties defines whether an initial conceptual direction is viable.

5. Conclusion

With the presented paper, we seek to clarify the importance of a systematic approach when transitioning from conceptual design to initial embodiment solutions, and suggest that creating an embodiment is a key step for all early stage design tasks. With this, we aim at balancing two important phases of every design process, namely creative problem solving activities and a more analytical approach. Based on a review of relevant, seminal literature, we derive a mental framework that structures relevant reasoning steps when thinking about initial physical structures, the major aim being a suitable 'wayfinding' in an ill-defined solution space rather than putting emphasis on the optimisation of solutions that have been chosen based on vague arguments and cognitive biases in misunderstood concept choice procedures. At the same time, we would like to underline that the individual thoughts that form the basis for our framework are not new, nor does the paper present empirical evidence. Instead, the framework is deduced from previously presented research. However, we hope that our understanding of the embodiment task might stimulate further discussions, and can ultimately help bridging the current gap between the conceptual exploration of ideas and the subsequent design of a satisfactory or even optimal technical solutions.

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