Chapter 2
Is Engineering Design Disappearing from Design Research?

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Abstract Most systems and products need to be engineered during their design, based upon scientific insight into principles, mechanisms, materials and production possibilities, leading to reliability, durability and value for the user.

Despite the central importance and design's crucial dependency on engineering, we observe a declining focus on engineering design in design research, articulated in the composition of contributions to Design Society conferences. Engineering design relates closely to the 'materialisation' of products and systems, i.e. the embodiment and detailing. The role of clever materialisation is enormous where poor engineering will often manifest in a multitude of consequences for downstream activities.

In this article we will draw a picture of what happens in the embodiment phase of designing, try to create an overview of current understandings and sum up the challenges of proper embodiment. Embodiment design is just as intellectually challenging as conceptualisation but seems much more engineering dependant and intriguing in its complexity of dependencies and unsure reasoning about properties by the fact that often a multidisciplinary team is necessary.

This article should be seen as the fertilisation of this theory and terminology barren land, inspiring researchers to work on embodiment and detailing.

2.1 Disappearing Engineering Design?

Herbert A. Simon argues "that design is the central activity that defines engineering – or at the very least, distinguishes it from the "pure" sciences – because the role of engineering is the creation of artefacts" (Dym and Little 2000). We would add that design is much more than engineering and that it takes much more than engineering to create a successful product. But when it comes to design, the embodiment phase, is what distinguishes engineering design from any other form of designing.

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Design research is composed of at least two sources: The nature of the artefacts to be designed (and produced) and the nature of human designing. Hubka (Hubka 1973) created Theory of Technical Systems, which we see as a generalisation of engineering insight, but formulated for the goal of synthesis. His theory structures different aspects of artefacts and creates the link to engineering knowledge. Early ICED conferences in the 80'ies were open to engineering topics and especially the collection of topics we today call Design for X (DfX). A review paper on the content of ICED conferences' (Andreasen 2001) showed that Design for Manufacture had a peak occurrence in the 90'ies. In another review paper on the merits of the Design for X Symposia (Andreasen et al 2006) arranged by Professor Meerkamm over a 20 year period (1990-2009) it was concluded that the focus on Design for Manufacture and Cost was only sparsely treated. It seems that industrial focus also is weakened due to preferences for "low wage country" manufacture. A revitalisation of Design for Manufacture may come from module oriented development and manufacture, which is still in its infancy.

Another trend was observed from research presented at the summer school on engineering design research (SSEDR) and a number of PhD-examinations. We see here a tendency for students to prefer topics which are utilising information technology and which are treating information management aspects of designing; unfortunately this preference is not combined with an insight into the content of the information, the activities performed or the ability to articulate what is going on. The students' preferences may be explained by the problems of capturing, understanding and adding original thoughts to engineering design projects in a relative short study period, partly due to their asynchronous nature.

Of course many contributions are related to engineering design at our conferences; our concern is the area of design, which is unique to engineering, namely embodiment design. Therefore we will elaborate on the delimitation, identity, content and importance of embodiment in the following sections.

2.2 The Starting Point for Embodiment

The starting point of embodiment is not easily defined for several reasons which we will comment upon here.

Most concepts are only partially new concepts, thus it may be that only the subsystems or features are conceptually new and carry "the differences that matter" (Hansen and Andreasen 2003), and the rest of the concepts will be "carried over" or re-used from previous designs. This makes the starting point of embodiment diffuse.

The same aspect we find in the decomposition pattern shown in figure 2.1; at each function level (or systems level), for instance in car design, we actually find the pattern of *synthesis* repeated: Concept – Embodiment – Details, which means that we can't draw a line on the time axis telling where embodiment starts and ends. This has large implications for engineering design project management, where attempts are often made to use these phases to form management style stage gates (Howard et al. 2008). This is one possible cause of the confusion and the inconsistent interpretation of these terms. As the pattern of decomposing and composing the embodiment phase is diffuse; we need to find a demarcation line between conceptual and embodiment design. We suggest that the phases be defined by the dominant activity, where point 'X' in figure 2.1 marks the transition from conceptual to embodiment design. Thus embedded in the embodiment phase we find tasks of conceptualisation of lower system level organs (function carriers). Finding the real shapes and distributions of the curves would make for interesting research.

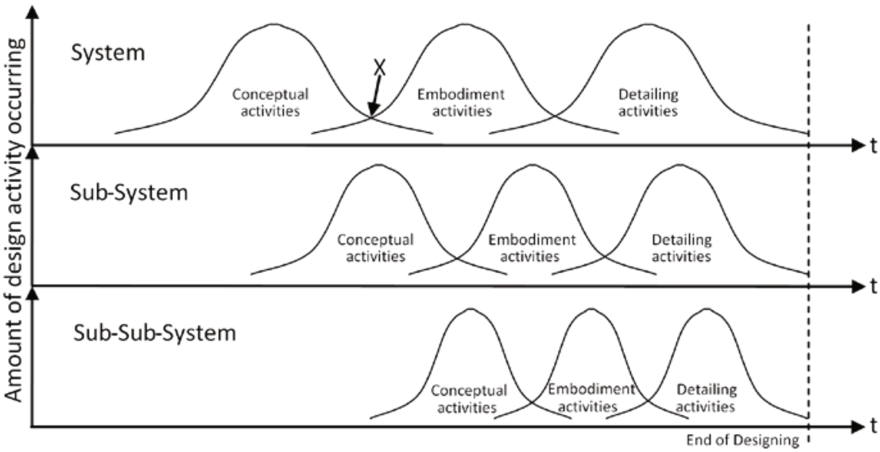

Fig. 2.1 The design activity decomposes into several levels of repeated design phases

To conclude: The starting point for embodiment is an inhomogeneous definition of the design, partially described as new concept(s), partly as carried over, embodied sub systems. Therefore the embodiment stage has to start with an overall definition of the embodiment, a structural scheme or architecture, to be filled in during the design activity.

2.3 What Happens During The Embodiment Stage?

Embodiment follows after conceptual design and is followed by detail design, claim Pahl and Beitz (Pahl and Beitz 2007), even if we often see necessity to make embodiment design work before a concept can be released. They see embodiment as composed by determination of preliminary layout and definite layout. Layout design is creating general arrangement and spatial compatibility, preliminary form design of components fitted to a production procedure and provides solutions for any auxiliary function. The definitive layout shall allow a validation of function, durability, production, assembly, operation and cost.

Ulrich & Eppinger (Ulrich and Eppinger 2004) call what follows after concept development, System-Level Design and Detail Design. The first activity contains product family considerations, creating of a so-called architecture (might be modular) of sub systems and interfaces, considerations on supply and make-buy, elaboration of assembly scheme and finally service and cost analysis.

Ullman (Ullman 2009) distinguishes between conceptual design and what he calls product design in a similar way. He says: "..the evolving product will be composed into assemblies and individual components. Each of these assemblies and components will require the same evolutionary steps as the overall product". Ullman sees product design as being composed of new design and re-design tasks.

Birkhofer and Nordmann (Birkhofer and Nordmann 2006) combine embodiment and detail design with the area of machine elements, i.e. the systematisation of basic, frequently used, low systems level solutions in mechanical products, like connections, clutches and shafts. Their approach may be seen as a 'bottom up' approach to embodiment: The better insight one has into known solutions, their mode of action and their dimensioning, the better the embodiment design will be performed.

These four textbooks unfold many characteristics of embodiment, but so to say without any articulated theory or models which can explain the transformation from concept to a structure of specified parts. In the terminology related to the Domain Theory (Andreasen 1980) the design activity is seen as the creation of three types of system structures: an activity structure related to the use of the product, an organ structure focussing upon the pattern of functions, organs and their function relations, and a part structure (parts and interfaces) created during the embodiment activity. Though this theory goes into much detail, there remain important open questions:

- Is embodiment reasoning of a different from conceptual reasoning?
- How is function determination and organ structure transferred to a structure of parts whilst explaining part interactions?
- What is created during embodiment other than layout and 'part drawings'?

The following sections will detail the most important aspects of embodiment design, namely, function reasoning (section 2.4), structuring (section 2.5), property reasoning (section 2.6) and part design (section 2.7). The intention is to consolidate the above questions, not to answer them.

2.4 Function Reasoning

A well-known design reasoning pattern has been formulated by Gero (Gero 1990) in his FBS-model (Function-Behaviour-Structure), where the reasoning from required function to the product's expected behaviour is followed by a jump to imagined, found or synthesised structures or solutions. The premise of the theory behind the FBS model is, that you are unable to determine what the function of a structure is, without first postulating a behaviour for the structure. Also, it is not possible to reason from a function to a structure without first conceiving of a behaviour to fulfil the function.

We see function reasoning as involving the identification and synthesising of the product's aim, for which, natural language is very supportive, particularly in the process of imagining, foreseeing and articulating functions. We also state that function reasoning is composed of two patterns answering substantially different questions:

1. What do we want to do with the product?
2. What do we want the product to do?

Gero's model seems to cover the second question, where 'structure' in his model relates to the product's structure (it might be organ structure or part structure). But we may also see Gero's model as being related to another structure, namely the man/machine structure or system, thus the function reasoning regards 'what we can do with the product'.

An example, inspired from Dym & Little (Dym and Little 2000): If we are to design a ladder we face the problem: What actually is a ladder? What can we do with a ladder and how does the ladder contribute? When the ladder is used the person is situated in a higher position, but the ladder is passive. How do we articulate its function? "Allow person to rise to a higher position"? And when the person stands there: "Support person"? Shall we add more functions: "Allow transport", "Foldable"? Each of these formulations creates different pictures in our mind.

Gruber (Gruber et al. 2010) claims that the design process of a car's front door contains the following stages: Forces - Topology - CAD - FEM - Part solutions - Validation and Testing. It means that he, reasoning as a supplier, sees the door's main function as "to protect passenger". You may say that the door should deliver the functions "allow embarking", "protect against weather" and "allow locking" of the car space, but we see here the effect of car safety considerations, leading to building in a safety beam and dimensioning for energy taken up by collision.

The other pattern of function reasoning relates to the product as a structure of organs, which through causality creates the functions of the product. This reasoning is composed of finding organs able to realise certain functions, and composing these organs into a structure.

An example: When considering a portable indoor elevating platform, the raising effect may be created by organs like a motor and transmission which deliver forces to a bar mechanism which holds the platform. The output effects of each organ shall correspond to the necessary input to other organs.

Function reasoning starts in conceptualisation and continues into the embodiment phase leading to the structuring of parts.

2.5 Structuring

In the conceptual phase it is decided how the design will be used and what the product shall do. The higher levels of the organ structure may also be determined, but as mentioned above this structuring is not finalised; lower level organs may appear in the embodiment and need to be composed into the organ structure.

Figure 2.2 shows a concept (a) for a milling fixture, which shall fixate four of the items shown in b. The functions and the corresponding (very principal) organs are explained in a. Some of the necessary details, which are not shown in the concept, are shown in c and new functions/organs are indicated by an asterix. The dimensional layout in d shows the part structure. Also here new functions/organs are indicated by asterix.

Determining the part structure is the dominating task in the embodiment phase. The transition from organ to part structure is a total re-arrangement, because a single organ may be realised by several parts, and a part may contribute to more organs. The part structure is not causally determined by the organ structure, but shall respect and realise this structure. In structuring the activity the designer may re-use substantial percentage of a past design, along with components, supply parts and standard parts; thus make-buy considerations are of great importance.

Today 80% of a German car is designed and produced by suppliers. We have already seen the complexity of embodiment design; imagine it split up in the transition from concept to embodiment in separate tasks and teams, responsible for sub systems' conceptualisation and embodiment, which shall show integrity and performance in the final product.

The design of modular products is a special situation where a modular ture is created and each module is a system element in both organ structure (by ing ideally seen a one function element) and part structure (by having standard terface).

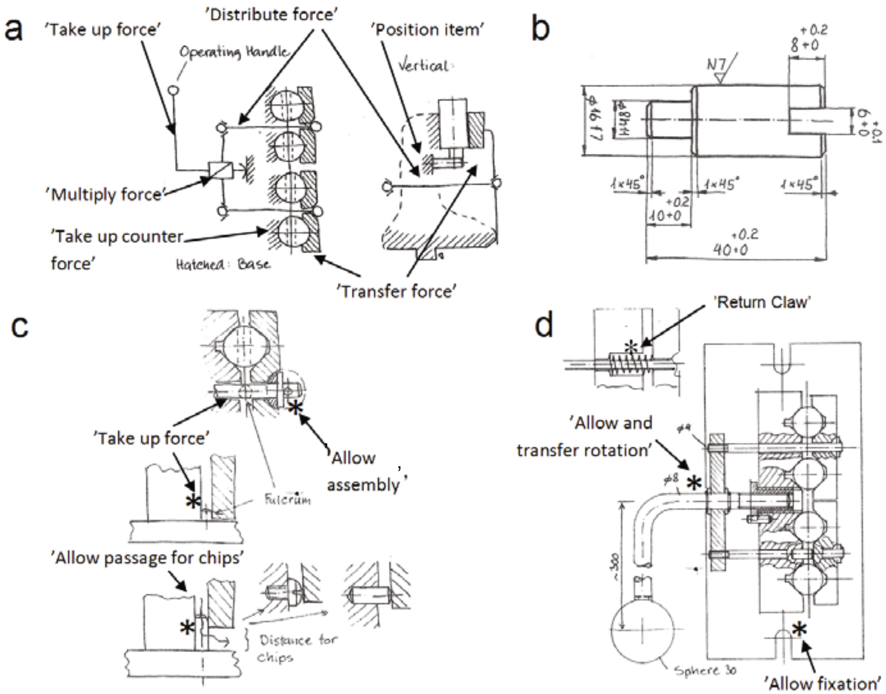

Fig. 2.2 Concept and embodiment of a milling fixture, see the text for explanation (Hubka et al. 1988)

Before CAD was introduced the normal working sequence was to elaborate on partial solutions of the concept based upon sketches and then to work out a layout, namely a scaled drawing showing the spatial arrangement of parts and their interfaces, see example in figure 2.2. Based upon the layout, the single part drawings were worked out and at the end, as a check, the assembly drawings were worked out based upon the machine drawings.

Research on the DfX-areas, mainly Design for Manufacture and Assembly, has shown the strong influence from the parts structure on the conditions and operation of the downstream activities of the product's realisation and life phases (Andreasen et al 1988, Olesen 1992). So certain structural properties are preferable to ensure alignment of the product's structure to the life phase systems and their activities. Let us mention some:

- When the product has a 'stacked structure' the assembly system can be a simple one-directional device (Andreasen et al 1988)
- It may be preferable to create the product's frame so that sub assemblies can be mounted on this frame in one layer only (it means no sub assembly is mounted on another sub assembly), benefiting both assembly and repair.

- A modular structure (US: architecture) may lead to benefits for development, supply, manufacture, distribution, maintenance, environmental effects etc. (Erixon 1988)
- A product family architecture may be utilised for enhanced alignment of the product to the manufacturing system's assets (platform thinking).
- Certain types of embodiment solutions, for instance for gear boxes, tube connections, car bodies, scaffoldings etc. appear in a limited number of variants, building modes (German: Bauweise). Choice of a certain Bauweise instead of starting with a 'neutral geometric design' may be a smart start on embodiment design (Mortensen and Andreasen 1999).

These fragmented examples belong to a higher level of complexity that concern reasoning about the embodiment of the product concerned. The reasoning is expanded to the product's life cycle phases, where the product's 'fitness for life' is determined by DfX efforts and proactive reasoning and scenario creation about what might happen in the life phases. And the reasoning is expanded to multi product development, i.e. alignment of a company's products, purchasing, facturing, distribution and sales efforts. In this higher complexity the theory of dispositions proposed by Olesen (Olesen 1992) plays an important role for plaining the dependencies between the areas.

2.6 Property Reasoning

Designing is traditionally seen to be governed by goal formulation. Beside a formulation of a team's task and the ideal business result, the goal formulation contains a list of requirements related to the ideal product solution, setting requirements for a product's properties. When a synthesised solution appears, articulated by its characteristics, the designer should be able to reason about this solution's properties and mutually compare alternative solutions to find the best solution.

Any organ has a main function and a set of solution specific properties follow this function (Hubka 1973). A simple liquid/glass thermometer may be specified to have high linearity, low zero fault, low temperature influence on its accuracy, quick response etc.; all these properties are specific for a (glass) thermometer and will govern the design process of a thermometer. Through the years, industry has collected knowledge which leads to highly delicate and precise products by understanding these function related properties. In the example in figure 2.2 we see how functions and organs have been added to the sparse set of functions shown on the concept. The main property of the fixture is "precise fixation", followed by "ease of loading/de-loading". These properties can't be evaluated from the concept sketch. Actually the property 'ease of loading/de-loading' is carried by some of the added sub functions, for instance how easy chips are removed by means of providing space for their escape and the returning the movable clutch parts by means of a spring.

Thus we are here confronted with another basic pattern of design reasoning, namely property reasoning. The pattern is well-known from the QFD method, where required properties are articulated by the 'voice of the customer' and related to the characteristics, features or properties of the product to see how well the product satisfies what the customer wants or how we can resolve complaints.

However, the QFD method proposes a very simplistic way of reasoning, as if it were evident that we can see how the product satisfies requirements or where certain properties are realised in the product. But important and complex properties, such as: reliability, utility, safety, comfort etc, in the design of a car for instance, can only be traced to the car's embodiment if we establish phenomena models of how we see these properties being realised. For the phenomenon 'car safety', the content of the phenomenon model might be the perception of collision safety ised by energy absorption, proper visual view by seat and window positions, or lock free braking obtained by ABS brakes. Thus, it is not a single model but a choice between many in order to find the best way to build in safety. Each ing of a phenomenon model and choice of means for satisfying the required erty may lead to new functions and parts, and may influence parts which have tasks not directly related to safety.

Embodiment as we see here is characterised by a difficult pattern of finalising the function reasoning and operating in the complex property reasoning pattern. Two challenges for the designer are added here. The first one is 'trade off', a very important aspect of property reasoning. This is when two or more properties are in conflict for a design and a decision must be made as to which to prioritise. It is not well understood how often designers make trade off, how they reason about it and how smart trade off may be the core of a new successful product concept.

The second challenge is the management of changes which is a time, cost and risk loaded topic in industry. Changes propagate through the part structure and need delicate adjustment, but they also disturb the property pattern often in a not easy to justify way.

2.7 Part Design

The part structure itself consists of parts in a spatial arrangement with physical interfaces. Therefore certain surfaces of the parts serve this interfacing, influencing the form, material, surface quality, dimensions and state of the parts, i.e. the characteristics of a part design as pointed out by Hubka (Hubka 1973).

The design procedure leading to a part's design has been treated by Tjalve (Tjalve 1976), who points out how to reason from the organ's characteristics to necessary part characteristics like function surfaces, interface surfaces, material fields etc. and to identify free surfaces which leave possibilities for fitting the form to a specific manufacturing technology.

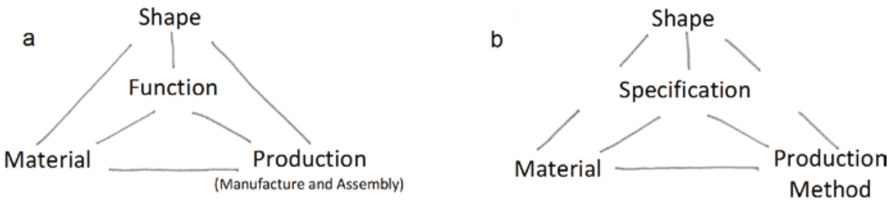

Fig. 2.3 Ullman's (a) and Jacobsen's (b) proposals for part designing (Ullman 2009, Jacobsen 1989)

Ullman (Ullman 2009) claims that "Refining from concept to product requires the consideration of four basic elements" shown in figure 2.3(a). He calls these types of reasoning for "Concurrent Design". It is interesting to compare with Jacobsen's model (Jacobsen 1989) figure 2.3(b). We believe Ullman's illustration shall be seen as rhetoric, because shape and material necessarily relate to one part, while function can't be directly related to a part. Jacobsen's illustration operates with a to 'be worked out specification' of what the part shall do, depending on the organ and the part interfaces (Jacobsen 1989).

2.8 Embodiment and Verification

When does embodiment finish? Many scholars see the detailing as the part oriented aspect of embodiment "in which a very large number of small but essential points remain to be decided" (French 1985). Other scholars focus upon the delivery of a complete set of drawings specifying the production of the product.

Can't we formulate a more strict description of an embodiment's result? In the past the finalisation of product development was traditionally the delivery of drawings. Today's insight into integration asks for overlapping design and production activities and early establishment of sales system, demanding delivery of preliminary designs and verified performance parameters for use in the sales promotion.

Verification means to ensure that you have built the thing right, asking: Does the product have the expected properties? Are we able to produce the product? These questions force companies to perform one or more verification activities based upon prototypes, pre-production and tests, which again leads to change or adjustment of the design. So it is wrong to see embodiment and engineering design as an isolated design matter. There are necessary iterations with production and the context reality which are necessary before ending the detailing.

The content of detailing seems to be an arbitrarily defined finalisation of embodiment. Of course there are tasks of creating formal production specifications but this does not really make the argument for a separate detailing phase. The proper final clarification and validation in dynamical cooperation with production, sales and distribution is much more important. To take into account these characteristics the final phase should be called 'Implementation Design' in line with previous research (Howard et al. 2008).

2.9 Nature of Human Design

This article is based upon several recognised theories but for the main part is a "model based theory" or theory of models based upon mental constructs which we (and maybe others?) believe will be productive in the minds of a practicing designer. We therefore derive and point out central steps of reasoning in embodiment.

In the transition from concept to part structure which was illustrated in figure 2.2 but actually as 'post mortem' pictures, not as explanations, we focus on a complex field of property relations, where every single required property is composed of sub properties and contributions from functions, components and parts, which may be scattered all over the product: the property field. At the same time we can focus on every single function and organ where certain function related properties shall be realised for this organ's proper performance. But actually these considerations are speculations: How does the designer do this? It is an open question.

Do they actually skip function and conceptual reasoning by making concrete part oriented design and check the resulting properties in a trial and error approach? How do they perceive of problems and tasks? Are they much more result oriented than design methodologies' problem orientated approaches dictate? How do they tackle the very high complexity of multiple criteria with their satisfaction spread out over a complex composed part structure?

Birkhofer (Birkhofer 2010) suggests that methodical work postulated by other researchers is considered by many developers to be "against their nature". It means that developers create a work practise, where it is difficult to bring in new terms and structured understanding. In education the students show no negative reactions to methodology; but they are not easy to motivate for carefully performed detail design.

2.10 The Challenges in Embodiment Design

We believe that current design methodology neglects the proper nature of embodiment and that CAD systems' abilities make it appear as if embodiment is properly supported. But one of the symptoms of the problems is the overwhelming number of design changes we see in industry. A recent study (Vianello and Ahmed-Kristensen 2010) has highlighted the extent of the design changes, stating a total of 1510 design changes were recorded over 8years of developing a Rolls Royce aeroengine, 79% of which can be traced back to systems level design and detailed design.

By consolidating and reasoning from the elaboration above, we see the following topics as central and challenging in embodiment design:

- To apply and develop engineering insight in embodiment and to keep track of the reasoning behind design decisions.
- To include long ranging influences and effects into the embodiment activity for beneficial downstream activities, especially to master structural relations between product and life phase systems.
- To master function reasoning and property reasoning and to keep track of this reasoning (designer's intent) both in the structuring and part design operations.
- To support teaching in this area by agreeing upon basic concepts and find ways of training function and property reasoning.
- To master the influences from multi product development, modularisation and platform thinking in the embodiment design process.

The effects of enhancing focus and competences in the embodiment area should be measurable in the following places:

- In the competing edge of products, concerning performance, reliability and value related to functions and properties.
- In the companies' internal efficiency by creating alignment and managing the complexity of embodiment.
- In the external effectiveness of offering users more attractive product-related operations and services throughout the product life phases.
- In the radical reduction of number of design changes from improper change operations and lack of control of the propagation of changes into the property field of the product.
- In the efficiency of growth of a company's product range and versatility.
- In product recall reduction.
- In the reduced repetition of design work.
- In the efficiency in design communication and task specification.
- In better informed trade-off decisions for both parts and structures, enabling trade-off of sub-system level efficiency for greater system level efficiency.

Of course these expectations are dreams from our side and the deficits are postulates for which many scholars work hard to try to deliver such solutions. However, for now at least, this remains one of the greatest challenges of '*engineering* design research'.

2.11 Conclusion

Even if the use of information technology has revolutionised designing and today is indispensible, many remaining problems can't be resolved by the regulation of streams of information, but need a closer understanding of the matters. It is our observation that embodiment and detailing is surprisingly a theory and language empty area where reasoning about function, structural and property aspects is unsupported and the design process is actually not well understood.

Our article is an answer to Professor Birkhofer's demand to elaborate on challenges in design research. We have answered related to a sub area of design research, namely embodiment, based upon personal opinions, a personal way of articulating embodiment design and a none-documented set of statements on state of the art and challenges. We hope the article will be read for inspiration and that researchers will see challenges in verifying or falsifying postulates and maybe work on what we see as challenges in embodiment design.

2.12 Afterword

During the career of Professor Birkhofer a great paradigm shift has occurred, from design practice to design research, from practice knowhow to models, methods and knowledge. During this time we have faced changes due to globalisation and the dramatic impact of both the technological and the digital information age. Despite these crucial times in the history of engineering design, huge headway has been made. Design has a clear and established place in product and technology development and the explosion of work describing the design and its processes have enabled communication and educational improvements both within and across its disciplines.

It is with great pleasure we contribute to this book on design research. One of the weaknesses of our young research area is that we have not yet found a way to communicate of our belief on central contributions, identify a powerful foundation and identify important directions of development. It is the merit of Herbert Birkhofer that he is in the front of challenging our research activities, requesting research consolidation and showing new directions, especially in the engineering oriented dimension of design and understanding of human design.

We believe this collection will be a valuable platform for development, not a closing balance for a period of efforts.

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