DESIGN METHODS AND THEIR SOUND USE IN PRACTICE

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Abstract: *Design methods have a great potential, but numerous academics have pointed out that they have not had the expected impact on industry. The paper highlights the need to improve the existing measurements of the impact, and discusses about when to use methods, and how to enhance the usability of methods for their sound use in practice. The discussion is supported by data collected through cases studies in industry and a design experiment. It is important to identify the types of design problems that methods are useful for, and to adapt methods to the specific problems without risking the results reliability.*

1. INTRODUCTION

One of the aims of design science is to suggest and develop ways in which the knowledge about the design process can help to improve the products resulting from designing, both in the quality of the objects and/or in more rapid and rational procedures [1].

The engineering design process has been described in numerous design models, the majority of which are step-wise processes of an iterative nature and prescriptive character. Some models explain the need to undertake in a given order different stages of product design (specification, conceptual design, schematic design, etc.). Other models, the design methods, concentrate on what can be regarded as design activities (data collecting, specifying, idea generation, synthesing, evaluating, concept selection, analysing failure modes, etc.).

Design methods are common-sense systematic techniques that 'attempt to bring rational procedures into the design process' [2]. They mostly originate from observations of best practices in industry [3]. Other times, they have been created to assist designers in undertaking tasks that were not being undertaken before. Design methods are not concept modelling tools that require a pre-conception of what to represent, they are the actual techniques to conceptualise what must be designed and how to realise it [4]. The design methods generated in the field of engineering design are mostly domain-independent, in contrast to the domain-dependent analytical methods of traditional design [5]. A comprehensive overview of existing design methods can be found in sources from the field of engineering design, such as [2, 6, 7, 8, 9].

Design methods have a great potential, but numerous academics have pointed out that they have not had the expected impact on industry, e.g. [10, 11, 12]. Part of the research community contends that this is because of weaknesses in the way design methods are developed or transferred (lack of computerised support, inadequate definitions, unsuitable scalability of examples, and inappropriate selection) [4, 10]. Other academics believe that design methods constitute by definition an erroneous way to support designers [13, 14].

Empirical data points out that there is a bit of truth in both asseverations. On one hand, there are situations in which design methods are not the most suitable way to assist designers. On the other hand, there are design situations in which methods can be useful, and their contribution is more valuable in design the more suitably it is developed or transferred.

The objective of this paper is to present the data that has lead to these conclusions and to show examples that illustrate the proposed ideas. The data has been gathered in several case studies in an automotive company and through the analysis of a design experiment. The paper starts with a discussion of the purpose and nature of design methods, with a literature study of the impact of design methods on industry, and some findings regarding the forms of impact. It continuous exploring the problem of when to use methods and with descriptions of how methods are being used. Finally, conclusions are drawn regarding the sound use of design methods in practice.

2. DESIGN METHODS, THEIR PURPOSE AND IMPACT ON INDUSTRY

2.1. Design methods as view of designing

Designing is not a new practice. Craftsmen were able to produce beautiful and complicated objects without the need to draw them because the knowledge behind a crafted product is the result of numerous trial-and-errors over many centuries [7]. Car manufacturers in the 19th century and the beginning of the 20th, who designed cars under commission [15], started to make scale drawings of what was to be built and to plan the production process. The trial-and-error activity was undertaken before production. The scale drawing was used for experiment and change, bringing new possibilities like division of labour of production work, construction of bigger artefacts, etc [7].

Although attempts to improve design operations must have existed centuries ago when people started to design, the topic has only been researched the last few decades [16], when products have become too complex to be developed through 'wholeist' designing-by-drawing. Abundant literature in the 80s and 90s showed that the best performing manufacturing Japanese companies could credit part of their success to their attention to design operations [15, 17].

Supporting designers requires an understanding of designing, what is subject to subjective interpretation. Eckert et al. [18] point out that whereas most practising engineers look at design as a chain of processes to generate solutions to identified needs, sociologists consider designing as a social process of negotiation, and psychologists as the sum of individual mental processes.

Therefore, design methods are just a simplifying way of understanding the complex reality of designing; although it should be noted that it is the simplifying way that seems to better suit the way engineers think.

2.4. The purpose of design methods

Originally, the purpose of design methods was to introduce rational procedures to design because the traditional ways of doing design, design-by-drawing, were found to be inappropriate for an increasingly more complex design activity [2].

Traditional design was characterised by drawing a tentative solution to deal with the complexity of the task. This solution is a way to explore both the situation and the design [2]. When this simplifying strategy does not deliver a solution matching the problem, the designer then transforms the design, sometimes improving the previous design, others creating a completely new variant [7].

For the development of increasingly complex solutions a systematic approach was suggested to be more appropriate. The then new complexity of product design was described by Pahl and Beitz [9] as being characterised by:

– The necessity to use solutions again

'In original design an ordered and stepwise approach, even if this is on a partially abstract level, will provide solutions that can be used again.

Structuring the problem and task makes it easier to recognise application possibilities for established solutions from previous projects and to use design catalogues',

– Increasing use of computer support for product models and division of labour

'A design methodology is also a prerequisite for flexible and continuous computer support of the design process using product models stored in the computer (…) Systematic procedures also makes it easier to divide the work between designers and computers in a meaningful way'

Design methods are models that plan and structure the design activity in steps. The question then is if these step-wise procedures simplify the complexity of design more effectively than traditional methods.

2.5. Literature on the impact of academic design methods on industry

Quantitative cross-industrial studies on the use of methods in industry have been done by diverse authors. Araujo and Benedetto-Neto [19] reported a survey with questionnaires answered by 27 companies in the UK, and interviews with 13 companies. They concluded that many companies were unaware of the potential benefits of available methods, that the extent to which a company utilises methods is strongly related to the annual turnover, and that the perception of methods contributing to success was enhanced when methods were implemented on a computer and when Total Quality Management (TQM) was implemented as a management strategy.

Grabowski and Geiger completed a 1995 study using questionnaires and reported the results in a German language article, as cited in [12]. Originating from this 1995 study, a table reflecting the percentage of companies participating in the survey that regularly, occasionally, or never used design methods from a list of thirteen can be found in English [12]. Lindemann [12] comments how the questionnaire showed the industry not using methods intensively.

Cantamessa [20] studied the relationship between design support techniques and development performance. In his study, 98 companies answered a questionnaire reporting about the information technology and engineering methods they had used. He concluded that 'product design is a powerful strategic asset in management's hand', but that it does not 'per se warrant the business success of a firm' [20]. He argued that studies on the impact of design support techniques cannot be separated from a complex network of interactions between different assets.

These three studies (Araujo and Benedetto-Leto's, Grabowski and Geiger's, and Cantamessa's) contain a list of methods being used in industry. The analysis of the impact of methods in the three cases was done at a cross-industrial level, as derived from a study involving a considerable number of companies.

2.6. Findings regarding the impact of design methods in the automotive industry

In a case study, conducted while sitting in an automotive company, by means of interviews mainly, complemented with internal document analysis, and informal conversations, it was found out that the influence of design methods takes place in a variety of forms in practice:

- Sometimes engineers apply academic methods very similarly to the way proposed by academics. This is the case of methods like Failure Modes and Effects Analysis.
- Most often engineers apply methods that resemble the academic ones, but with modifications or incorporate features of academic methods the designers' own working methods. Examples of this type of use of methods and their consequences are given in section 4. They were typically concept selection techniques and brainstorming methods.
- Other times, methods are used once and never applied again, but can have a pervasive influence on the way designers think, as recognised by themselves.

Different types of methods implementation could also be deduced from the study:

- Top-down implementation of methods results from a strategic decision by management.
- Bottom-up use of methods occurs when designers themselves try to implement the use of some method. This is an indicative sign of the value of design methodology research in industry.

The results suggest that research on the impact of design methods should also be undertaken at the individual and group levels for a better measurement. Cross-industrial studies are necessary but not enough, since they can only provide results regarding the use of academic methods implemented in a top-down approach. Other ways to measure the pervasive influence of methods, the modified methods, and the methods used under the initiative of designers themselves, are needed to complement the cross-industrial studies.

This paper does not try to quantify this other type of use of methods, but to further explore the problem of the usability of methods and to provide details about how methods are applied in industry.

3. WHEN TO USE DESIGN METHODS

3.1. The constructivist view

Dorst and Dijkhuis [21] discuss two fundamentally different paradigms to describe design activity: one is the positivist view of design "as a rational (or rationalizable) process", which gave birth to numerous design methods; the other is the constructivist view of Schön [13, 14], who describes design as a process of reflection-in-action.

Constructivism, which was born as a reaction to rationalism, has provided important knowledge regarding when design methods are not useful. They distinguish between what has been called well-structured problems and ill-structured problems.

Ill-structured problems have been described as [22]:
- Being partly determined by defined and unalterable needs, or intentions
- Having a major part of the problem undetermined
- The designer is dominant in the sense that he provides the criteria on which the design is going to be judged.

Constructivists claim that design methods are only useful for well-structured problems, and that ill-structured problems require something like a framing [22]. The reason for this is that systematic models of design build on positivistic idealisations of designing, which fail to acknowledge the complexities of designing in practice (i.e. of solving ill-structured design problems). According to constructivists, the designers 'decides what to do and when based on a personally perceived and constructed design task' [23]. From that viewpoint, methods through their imposition of pre-determined steps disrupt any possibility of attaining creative results to ill-structured problems.

3.2. Findings in the influence of design methods on the creative process

In a design experiment [24], it was found out that some methods lead designers to change of frame more often than others, what could be interpreted as a disruption of the design activity by the imposition of steps. The methods that were tested in the experiment were:

- SCAMPER (Substitute, Combine, Adapt, Modify, Put to other uses, Eliminate, Rearrange), an idea-prompting checklist in the form of questions
- Visual stimuli, consisting of pictures related to the function and shape of the object to be re-designed.

The experiment showed that visual stimuli disrupts more often the own creative process of designers because whereas some SCAMPER questions were used as sub-frames of designers' own ways of framing the problem, the images were not. The images led the teams to be changing of frames continuously, without reaching a satisfying pair problem-solution.

According to Christiaans [25], the more time a designer spends in using his own frame of reference (or own way of understanding the problem), the higher the chance to achieve a creative result. Since, the experiment undertaken shows that methods can disrupt the creative process of designers, we can conclude that there is a risk that methods do not assist in the creative process, and what is worse, prevent from coming to creative results.

3.3. Difficulties in applying the definition of ill-structured problems

It seems, therefore, that methods can be counterproductive in some design situations. It is important to know when. The problem with applying the criteria proposed to distinguish between well-structured and ill-structured problems is that its use is only clear if the problems are in fact in one of the two extremes. For example, starting to redesign an artefact to fulfil a new function is clearly an ill-structured problem. The selection of the set of values of oil and filler level that optimise a rubber formulation with respect to cost, rebound, tensile and hardness is clearly a well-structured problem. However, in practice, there are problems that are difficult to classify using the criteria proposed, especially because the statement ‘having a major part of the problem undetermined’ is a subjective measure. The question is can those problems that fall in between well-structured and ill-structured problems benefit from the use of design methods?

An example of a type of problem that does not fit well in the well-structured/ill-structured classification of problems has been found in practice. It is the selection problem that engineers in the concept study phase of the car project deal with. In the automotive industry, off-the-shelf solutions strategies are the common way to approach product development (Figure 1). It involves new solutions for systems being developed independently of car projects. These new solutions are not implemented in a car until their feasibility and advantages relating to the old solutions are consistently proven, with few exceptions. Therefore, the objective of a car project is mainly to select the combination of off-the-shelf solutions for the systems of a car from the company ‘stock’ that better fulfils customer attributes, and to work with the systems up to a maturity and verification level that the company is certain it can release the resources and money to develop the car for production.

In the Concept Study phase, designers start with a list of attributes to be fulfilled, the previous model (which does not fulfil the requirements), and a number of available off-the-shelf systems that could serve to ‘close the gap’. They know from the beginning that it will not be possible to fulfil all the

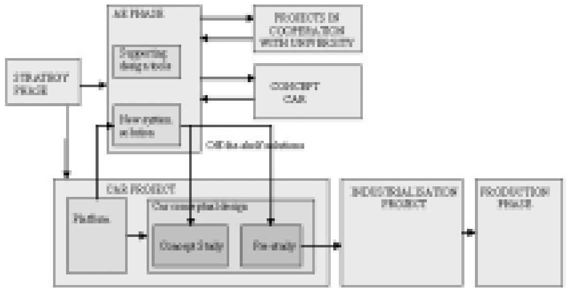

Fig.1. *Model of the design projects structure at an automotive company*

requirements, and designers will therefore have to be dominant in the sense that they have to decide what the satisfying pair of requirements and car concept will actually be. On the top of this, the governing process is the geometrical discussion of whether the different systems will fit together, requiring creative design to solve eventual problems in making the systems fit together in a car. This kind of problem has characteristics of both types of problems:

- The facts that the governing process is the geometrical discussion, and that designers have to be dominant.
- The fact that the number of solutions considered is limited, in the sense that only known solutions for systems can be used, sounds more of the well-structured type of problem; although it should be noted that these known solutions must be changed (redesigned) to make them fit in the car.

Typically, designers will develop various concepts and select the most promising. For this kind of problem, academic design methods are being used. The methods used are matrix-based methods for concept selection to guide the process of selection.

The conclusions are, therefore, that there are some kinds of problems that do not fit well in the ill-structured/well-structured classification of design problems, and for which, apparently, design methods are being useful. Thus, an important question is how often do designers face design problems of the well-structured type, of the ill-structured one, and of the undefined type? And what is the nature of other potential problems that may also be of the undefined type?

4. INCREASING THE USEFULNESS OF METHODS

This block of research was started unanticipatedly, while sitting in industry. After the formal interview mentioned in section 2.6, some engineers turned to the researcher for advice about the problems being encountered in the use of methods. Data about how methods are used in practice was collected from real-life examples. This collection of data is not part of a planned experiment where designers are asked to use methods. On the contrary, designers used methods on their own initiative. The main advantage of this research approach is that the obtained data derive from purely real design practice (as opposed to the artificial of experimental research).

Most of the methods which designers enquired about were for concept selection. As mentioned before, these methods are often used with ad-hoc modifications to adapt the method to their situation and understanding. Modifications to methods were found to normally produce two types of effects in the implemented method: unreliable modification of method and creative adaptation of methods. It can happen that in the same implemented method, creative adaptations and unreliable modifications occur.

4.2. Unreliable modification of methods

Unreliable modification of methods occurs when a method is applied to an unsuitable situation or with modifications that reduce its reliability. The Pugh-like method of Figure 2 is used here to illustrate the concept. It was used in real life to select an engine suspension.

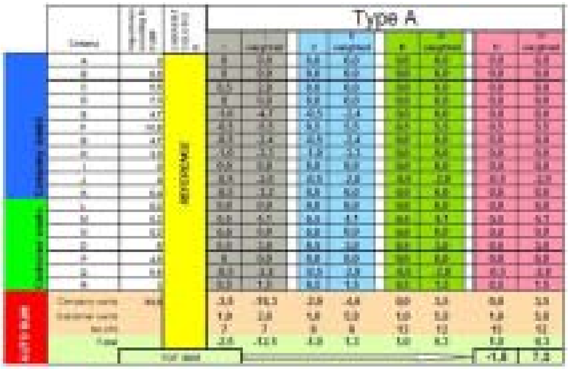

Fig.2. *Pugh-like method used in practice (from [26])*

This method was selected for use because the solutions performance was not precisely known, and it was more sensible to evaluate the alternatives in terms of better or worse with respect to a reference than in absolute terms. However, engineers soon wanted to introduce weighting, trying to reflect the importance of attributes and different levels of better and worse. This led to difficult to grasp numerical results. The engineers commented that they could not understand what, e.g., '-3,5' means in relation to '3,5'. They did not know if these numbers represented a big difference in real performance. This type of misuse of the Pugh method is very common and completely destroys its goal, i.e. permitting comparison without detailed quantifiable knowledge of the solutions.

Other observations of unreliable modifications of methods were:

- Numerical methods, such as weighting and rating, were used to select between concepts whose performance was not well known. Uncertainty in the performance of these concepts caused numerous changes in the numbers introduced into the method, with the obtained results from the different sets of values introduced being so different that the group stopped believing in the results the method could provide. Several ways for dealing with uncertainty in concept selection are suggested in the literature, such as sensitivity analysis [27] or PPCOc (Pluses-Potentials-Concerns-Overcome concerns) [28], which could have been more appropriate in those cases.
- The results from a paired-comparison analysis of product criteria are used as weights in calculating the weighted scores for concepts [9]. However, the only information that a paired-comparison analysis can render is the order of criteria importance. Providing a cardinal value to ordinal numbers leads to results lacking in reliability.
- Paired-comparison analysis is typically used to compare a high number of product criteria. The analysis results depend on the set of values used (product criteria in this case) [27]. If the criteria are not independent, unique, and static, the results lack reliability. The set of product criteria in industry, i.e. the criteria against which product performance is measured, is not only uncertain because it is difficult to grasp what the customer wants, but also dynamic [29].
- A common mistake with the Pugh-type of matrix is to believe that the results obtained by comparing different concepts with a reference can be used to compare the concepts' performance with each other. If the reference concept performs significantly bad, comparing the concepts with the reference will not highlight the potential differences in performance between concepts.
- The arithmetical mean is often used to calculate an overall performance of concepts having been scored with respect to different criteria. Finding the optimal solution through a weighted sum involves weights being trade-offs: to compensate for a disadvantage of x units for one criterion, and advantage of y units is required in another criterion [27]. When the good performance of a criterion does not compensate the bad performance of another criterion, as is normally the case for products, methods other than the arithmetical mean are better suited to calculate overall performance, such as the harmonic mean. The harmonic mean is implemented in the Microsoft Excel, i.e. the software typically used for matrix-based concept selection.

The engineers that approached the researcher to discuss the problems encountered with the usage of methods had already begun to use a method for the concept selection activity they were dealing with. The reason for asking for advice was that the obtained results were unexpected and did not suit the gut feeling of the team or of some of its members. The researcher was approached to explain why the method was delivering such surprising results. The engineers showed documentation about the method being used, and discussed the problem with the researcher. Solutions for the problems encountered were discussed using academic methods as exemplars [30], i.e. models against which other researchers or practitioners can compare their experiences and gain theoretical insights. The main challenge was to find the right methods to compare theirs to, since methods for concept selection are spread out in numerous publications.

After gaining some experience in "trouble-shooting" methods for concept selection, a decision tree for the selection of the appropriate method (and sub-methods) was designed. As it can be observed in Figure 3, for the selection between four methods for concept selection:

- At least 5 decisions regarding the type of method to be used have to be made to use ALUO or the highlighting technique
- At least 7 decisions for the Pugh method
- At least 8 for the Rating and Weighting method

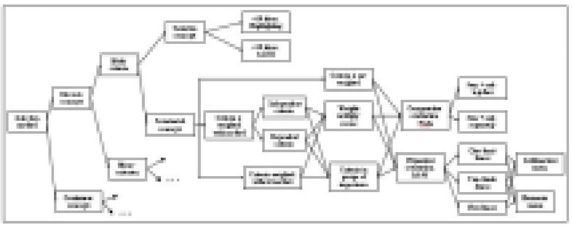

Fig.3. *Identified decisions for the conscious selection between the Highlighting technique, ALUO, the Pugh method and the Weighting & Rating method (from [31]).*

The ad-hoc modifications done by the engineers to academic design methods and their subsequent problems are not the only difficulties the apparently easy-to-use methods for concept selection can present. The unreliable modifications discussed here are just those more often observed in industry that the researcher had the opportunity to follow closely. To get an overview of the complexity of the subject the reader is requested to refer to literature where the suitability of methods for different conditions is compared, e.g. [27], and to consider the whole range of methods for concept selection reported in academe: the design evaluation display [32], the sensitivity analysis approach [33], the Property Based Model [34], the ellipses approach for uncertainty consideration [35], etc. Each of these methods has been envisaged and implemented to solve problems observed in real concept selection and presumably were not sorted out in other methods.

Therefore, we can conclude that design methods get easily misused, and that researchers should provide the means to prevent methods misuse.

4.3. Creative modification of methods

Modifications to methods have been found to lead not only to unreliable results, but also to creative adaptation of a method.

Creative adaptation of a method occurs when a method is applied to a situation with modifications that increase its value and without reducing its reliability. In those cases, engineers plan and structure their process of design creatively and situatedly.

Creative adaptations and unreliable modifications can also happen in the same situated method. For example, Figure 2 was previously used as an example of questionable modifications to the Pugh method, though some modifications enhance its value. For example, the criteria have been classified as 'company wants' and 'customer wants'. 'Company wants' includes product criteria related to strategic choices of the company, such as commonality aspects, core values, and production facilities. 'Customer wants' includes product criteria that have been identified as customer wishes. In making this distinction, the selection is done with a clear understanding of the level of achievements that different solutions have concerning short-term goals (satisfying the customer) and long-term envisaged assets (company wants). Additionally, the number of '0s' was counted, providing a measure of the type of change regarding the current paradigm concept, which is an important aspect often considered in the automotive industry. Therefore, these modifications increase the value of the method, since they include fundamental selection factors identified for the type of industry.

These findings show that design methods can be improved by adapting them to the type of problem at hand. The key question is then to support designers in the adaptation of methods without risking the method reliability.

5. CONCLUSIONS

The impact of design methods on industry remains unmeasured to the extent that the pervasive influence of methods and the use of methods under the initiative of designers themselves have not been largely explored.

For a better transfer of methods into industry, more should be known about their sound use in practice. Two issues regarding their sound use have been highlighted in this paper:

- It is sound to try to use design methods only when they can deliver a valuable contribution. For this, it is not only necessary to know the characteristics of methods, but also to be able to describe the nature of problems and how often the different kinds are faced by designers.
- When design methods are perceived by designers as being useful, it is sound to adapt them to the specific problem/company/industry. Patterns in the modification of methods should be studied to assist designers in *creatively* adapting them and in avoiding to risk the method reliability.

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