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ON THE SUPERIORITY OF OPPORTUNISTIC DESIGN STRATEGIES DURING EARLY EMBODIMENT DESIGN

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1. Introduction and Objectives

To support designers and to rationalise design processes, prescriptive design methodologies have been developed, which nowadays are the basis of design education not only in Germany. These Design Methodologies are mainly characterised by "[…] a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology, and from practical experience in different domains. It includes: plans of action to link working steps and design phases according to content and organisation; strategies, rules and principles to achieve general and specific goals, and methods to solve individual design problems or partial tasks." (Pahl & Beitz 1996, p. 10) However, from the beginning a distinct discomfort with the strict hierarchical nature of this approach has been articulated in particular by professional designers. As a consequence it has been emphasised that iterations are needed when applying this approach to real design processes: "[…] such strategies, and procedures based on them, should not necessarily be pursued in a strictly linear fashion. […] It is therefore important for a plan of approach to include iteration, the repetition of phases or steps, with those of little importance being passed over rapidly or even skipped." (VDI 2221 1987, p. 5) This recommendation has been added to the linear approach afterwards and almost no guidance or criteria exist for how to manage this in practice: how to decide when to deviate from the top-down approach and when not, which steps and phases to skip and which not. As a result, this methodology is still seen as being artificial, time-consuming and restricting and, therefore, is hardly accepted in an industrial practice.

Over the last ten years, empirical research has changed our view on individual design activity, challenging the hierarchical top-down strategy of Design Methodology, and proposing a more flexible and balanced approach. This contribution investigates the question what 'flexible' and 'balanced' actually means in this context and how the appropriate level of flexibility can be determined. To identify correlations between design procedures and design success in the conceptual and early embodiment design stages, we investigated the procedures of 71 engineering design students (83 evaluable cases) to determine the applicability and the success of Design Methodology in these stages. This paper presents some of the findings on the observed procedures and their effects on design performance, focusing on the early embodiment stage.

2. Empirical Design Research and Design Methodology

In the German discussion on Design Methodology– and in other international contexts too (for an overview see e.g. Blessing 1994 or Bender 2004) – a number of empirical research projects changed the way we look at individual design activity. Dylla found that two fundamentally different design strategies can be observed in early design stages, which he called *productive solution generation* and *corrective solution generation* (Dylla 1991, pp. 95ff.). Productive solution generation is characterised by the synthesis of several independent solution variants followed by an evaluation process leading to the selection of a promising solution to be further refined. Corrective solution generation starts off with one more or less concrete solution idea followed by a stepwise refinement until a solution of sufficient quality is reached. Dylla pointed out that corrective solution generation prevails significantly (81% of all observed generations had been corrective) although a productive solution generation strategy is strongly recommended by Design Methodology.

Fricke distinguished between *stepwise process-oriented* and *function-oriented* design strategies (Fricke 1996, p. 158). The stepwise process-oriented strategy follows a hierarchical and sequential plan of action, executing basic design operations step by step for all subsystems more or less in parallel. Within a function-oriented procedure design operations are carried out for one initial function or subsystem until a satisfying level of concretisation is reached before the next function is addressed in the same way. Fricke comes to the conclusion that the best design performance can be achieved by following a "*flexible-methodical proceeding"* (Fricke 1996, p 159), aiming at a "*balanced search*" for solutions (Fricke 1996, p. 163).

Günther identified personal characteristics of designers supporting design performance. These are in particular *professional design experience*, *high heuristic competencies* and a *low disposition for emotional stress*, *regression* (i.e. behaviour of escape and avoidance when facing difficult problems) and *resignation* (Günther 1998, pp. 64ff.). He also identified process characteristics that had a negative influence on design performance: *incomplete clarification* and *bad memorisation of requirements*, *wrong weighting of sub-problems*, *too early moving from concept to embodiment* without an elaborated concept and a *largely unstructured procedure* (Günther 1998p. 142).

Rückert showed in a field study into design strategies and performance of engineering design students that characteristics of the learning process are important for the efficacy of a Design Methodology Education. He found that a self-determined and flexible application of Design Methodology strategies led to better design results compared to the strict application of a Design Methodology, in this case the methodology proposed in VDI 2221 (Rückert 1997, p. 132). In addition, the acceptance of Design Methodology was significantly higher in the self-determined group (Rückert 1997, p. 126).

One central conclusion can be drawn from these results: the concept of strict hierarchical top-down decomposition seems not to be an appropriate model of design problem solving. The model neither describes reality nor is it suitable as prescription to support design. Therefore, more or less all authors come up with proposals of a more "flexible-methodical" and "balanced" (Fricke 1996) or "flexible solution-oriented" (Rückert 1997), adaptation of Design Methodology strategies, rules and guidelines. This leads to the interesting question what 'flexible' and 'balanced' adaptation actually means and how the appropriate level of flexibility and the 'right balance' can be determined. To answer this question, considerations from the field of action regulation theory and in particular considerations of cognitive planning and goal-directed activity seem to be promising to extend the understanding of individual design behaviour and its success factors (cf. Hacker 1999). Some relevant findings are discussed in the following paragraphs.

Hayes-Roth & Hayes-Roth investigated individual planning processes and introduced the concept of an 'opportunistic model of planning' to describe planning processes. They presumed that the cognitive activity of planning comprises a set of basic activities (in their terminology 'cognitive specialists') which have to be co-ordinated to succeed in planning. They found that "the activities of the various specialists are not coordinated in any systematic way. Instead, the specialists operate opportunistically, suggesting decisions whenever promising opportunities arise." (Hayes-Roth 1979, p. 275)

Guindon transferred these results to the (software) design area and described the concept of *opportunistic decomposition* instead of top-down decomposition for dealing with complex and ill-structured problems. She observed individual design processes, deviating greatly from top-down approaches without having negative consequences for design performance. "The analyses show that these deviations are not special cases due to bad design habits or performance breakdowns but are, rather, a natural consequence of the ill-structuredness of problems in the early stages of design." (Guindon 1990, p. 307) She comes to the conclusion that "[…] the early stages of the design process are best characterized as opportunistic, interspersed with top-down decomposition." (Guindon 1990, p. 336) In detail, “opportunistic design is characterized by on-line changes in high-level goals and plans as a result of inferences and additions of new requirements. In particular, designers try to make the most effective use of newly inferred requirements, or the sudden discovery of partial solutions, and modify their goals and plans accordingly. […] Opportunistic planning is in fact a more general type of planning than hierarchical planning.” (Guindon 1990, p. 337)

Visser underlines these findings and comes to the conclusion that “[…] even if designers possess a pre-existing solution plan for a design problem, and if they can and do retrieve this plan to solve their problem (which is often possible for experts confronted with routine design), *yet* if other possibilities for action ('opportunities') are also perceived (which is often the case in real design) and if the designers evaluate the cost of all possible actions ('cognitive' and other costs), as they will do in real design, *then* the action selected for execution will often be an action other than the one proposed by the plan (it will be a selected opportunity).” (Visser 1994, p. 235) In result “[…] even for experts involved in routine design, retrieval of a pre-existing plan does not characterise the organisation of their actual activity appropriately. Such a plan which, if it is followed, may lead to systematically organised activities, is supposed to be only one of various action-proposing knowledge structures.” (Visser 1994, p. 268) She identified *cognitive economy* as the most important category motivating designers to deviate from top-down strategies to opportunistic design.

One can discuss whether this descriptive research only identified the *most common strategies* or if it also can teach us the *best strategy* with respect to design performance. From a prescriptive point of view, one may argue that opportunistic behaviour might be very common under everydays’ constraints of professional design practice but that a deliberate step-by-step strategy nevertheless would lead more efficiently to better or at least more reliable results when applied consistently. Clarifying this question has been the main motivation of our research.

3. Questions and Hypotheses

To further investigate the question of ‘best strategies’ for design we focused our research on differences in individual design procedures, which can be observed when engineering design students are asked to solve particular design tasks from the conceptual and early embodiment stages of design. The latter is the focus of this paper. Following the theoretical concepts of opportunistic vs. hierarchical approaches and relying on existing empirical findings, we expected to find four individual types of ‘design styles’ for the early embodiment stage:

(a) *Hierarchically phase-oriented*: A procedure strictly following VDI 2221 which can be characterised as organised sequentially and hierarchically at the same time (cf. Fricke 1996). The process thus involves a combination of hierarchical decomposition and sequential goal accomplishment. Therefore a design activity is executed for all subsystems before the next activity takes place, which is again executed for all subsystems, and so on.

(b) *Hierarchically object-oriented*: An overall task can also be decomposed in terms of systems and subsystems to be designed. Such a design style would be characterised by the execution of all design activities – or subsets of activities within ‘hierarchical episodes’ – for one subsystem before they are executed for the next subsystem, and so on.

(c) *Opportunistic and associative*: This is a knowledge-driven resp. data-driven procedure following the concept of opportunistic planning, but interlaced with periods in which hierarchical approaches are applied, the socalled hierarchical episodes. Instead of starting with a hierarchical decomposition of the task, the designer may begin with a preliminary decomposition and then start elaborating a part of the system. A possible reason is that the designer remembered a suitable solution for this part and took this opportunity as a starting point. This is a mixture of a hierarchical decomposition with an opportunistic, local and bottom-up, proceeding. It is less guided by a total goal but more by the association between the step that has just been finished and the opportunity to do the same step again on a different (sub-)problem.

(d) ‘*Muddling through*’ or *trial and error*: From the point of view of action regulation, a trial and error-like procedure, hardly following any observable systematic or methodical guideline, should be identified. This involves a more or less unsystematic trying to cope with different parts of the system, different design activities and (sub-)problems instantly every time they occur or come to conscious consideration. This procedure also can be classified as extreme opportunistic but misses any kind of hierarchical episodes.

The main question we tried to answer was: are there any correlations between observed individual design strategies and the achieved design performance? The aim was to identify a ‘best strategy’ out of the four with respect to the achieved design performance.

4. Methods

A quasi-experimental research design was developed to determine the effects of individual design procedures on design performance in the early design stages. Engineering design students were confronted with standardised design tasks. Procedural variables of design activity were observed using photo-documentation and self-protocols. For analysis and categorisation of the individual design procedures, quantitative and qualitative methods were selected that were appropriate for the research design. The participants’ individual design performance was evaluated in three different objective categories using a formalised method based on value analysis. In addition, methods to identify the four different hypothetical design styles based on objective criteria have been applied (for more details of the applied research methods see Bender et al. 2001 and Bender 2003).

5. Results

We found a significant influence of the four postulated individual design styles on design performance in the early embodiment stage: strictly following the hierarchically phase-oriented approach lead to significantly worse embodiment designs (median about 50% of achievable maximum) compared to the other strategies. The hierarchically object-oriented and the opportunistic and associative group reached significantly better performance (about 70% of maximum performance). Even the group with the ‘muddling through’ design style did not achieve as worse an embodiment design performance as did the hierarchically phase-oriented group (Figure 1).

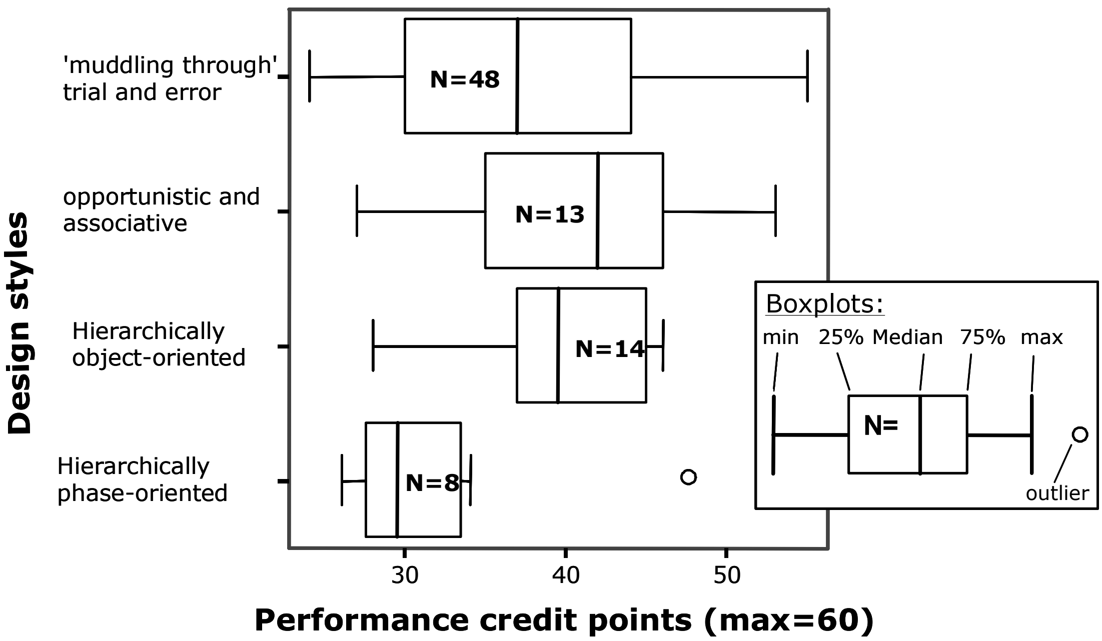

Figure 1. Design styles and design performance

Looking more deeply at these results, we found that there are considerable differences in the likelihood of achieving a certain performance when applying a certain design style. To determine these differences we used specific statistic measures derived from clinical research which normally are used to compare the relative success of two different medical treatments (for details see Bortz & Lienert 1998, S. 225.). The measure "rR" characterises the relative risk to achieve less success in one clinical trial group compared to another one, while "f" defines the reduction of the likelihood of failure of treatment in one group compared to another. Finally, the odd ratio "OR" correlates the success rates of two groups and therefore chartacterises the degree of superiority of the more successful treatment. We determined these measures to investigate the strength of differences between the observed design styles (a) according to the risk of failure – as measured by the likelihood to achieve a poor design performance below the 50% level of performance credit points – and (b) with respect to the likelihood to achieve a very good design performance above the 75% credit point level. (Table 1, all differences significant on $\alpha \leq 0{,}05$ level).

Table 1. Strength of influence of design styles on early embodiment design performance

Group differences	rR50	f50	OR50	rR75	f75	OR75
HP (N=8) ↔ HO (N=14)	3,50	0,71	6,0	1,23	0,18	2,80
HP (N=8) ↔ OA (N=13)	3,25	0,69	5,5	1,63	0,38	6,00
HP (N=8) ↔ MT (N=48)	2,67	0,63	4,3	1,14	0,12	2,08

The relative risk (rR50) to achieve a poor embodiment design performance below 50% of the maximum credit point level is about three times higher following a hierarchically phase-oriented (HP) design style compared to all other design styles – with a tendency to a higher superiority of the hierarchically object-oriented (HO) and the opportunistic and associative (OA) design styles. The likelihood of falling short of the 50% level of embodiment design performance (f50) is reduced about 60 to 70%. Finally, the three non-phase-oriented design styles are four to six times superior to the hierarchically phase-oriented one related to the 50% criterion (OR50).
Looking at the chances to achieve a very good embodiment design performance above 75% of the maximum credit point level, it becomes apparent that the opportunistic and associative design style is the most promising one. In this category the hierarchically object-oriented (HO) and the 'muddling through' (MT) design styles are – as measured by the relative risk (rR75) of falling short of the 75% level of performance – only slightly more successful than the hierarchically phase-oriented design style (HP). Also the likelihood of falling short of the 75% credit point level (f75) is only slightly reduced (about 10 to 20%). In contrast, this likelihood is about 40% reduced for the opportunistic and associative design style (AO). The odd ratio OR75 clearly underlines the strong superiority of the opportunistic and associative design style (OA): this design style is six times more successful compared to the hierarchically phase-oriented design style (HP) as measured by the chances to achieve very good solutions. The other two design styles are "only" two to three times more successful.
According to these results we are able to answer our main question mentioned above: flexible and opportunistic design strategies are obviously not only more common in real design processes but as a matter of fact lead to better design performance than the hierarchically phase-oriented approaches suggested by traditional Design Methodology.

6. Conclusions

Our research confirms the results of the many empirical studies showing that real design practice is much better characterised by opportunistic procedures and strategies than by strict hierarchical top-down processes. The outcomes of our study now lead one step further: we could confirm that these opportunistic design styles are not only more common but are also *significantly superior* with respect to design performance. In the early embodiment stage, hierarchically phase-oriented procedures lead to poor design performance, while a flexible adaptation of a systematic approach helps to achieve very good performance. 'Flexibility' here can be seen in two main directions: (a) approaching the design problem *hierarchically object-oriented* through decomposition of the design objects or (b) approaching the problem *opportunistically and associatively*, taking advantage of available and promising opportunities which arise during the process.
In our opinion, the object-oriented strategy is the most suitable for design education and training, while the opportunistic one – as a common strategy of design experts – can hardly be taught explicitly: it is the result of continuous improvement and experience in professional practice. However, to be open for, to look for and to assess opportunitities can be trained and supported already in university

teaching and shall not be suppressed by forcing the students to strictly follow the rules and guidelines of Design Methodology.

From a cognitive point of view, these two strategies seem to be the best options to cope with the complexity of design problems and to reduce 'cognitive load' in design problem solving. Thus, Guindon's, and Visser's concept of 'opportunism' as a natural consequence of the ill structured character of complex and knowledge rich design problems could be proved as valid for successful design heuristics. In our point of view, this concept is the most promising for determining what a flexible approach to a systematic design process might be in professional design practice and in teaching and learning design.

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