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A SYSTEMATIC APPROACH TO OBSERVATION, ANALYSIS AND CATEGORISATION OF DESIGN HEURISTICS

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1 Introduction

Improvement of methods and tools supporting the design process requires detailed understanding of successful design strategies. Therefore observation, analysis and interpretation of design styles and strategies within empirical design research are of high importance.

In this paper, the main objectives of empirical analyses of design procedures will be determined, potentials and limitations of different empirical approaches will be discussed and, based on results of earlier research, a systematic approach to observation, analysis and interpretation of design procedures within a laboratory environment is proposed.

This approach has been developed for and tested with a descriptive study into design strategies of novices and professional designers with the aim of investigating the applicability of classical design methods in the conceptual and early embodiment design phases. The study has been described in [1]. This paper therefore focuses on laboratory studies into design procedures, and gives an overview of the concept and the approach. Details can be found in [2].

2 Main Objectives

Some empirical studies into design are based on the hypothesis that design procedures will improve the result of the design. There has been a number of empirical studies examining this relationship, establishing a tradition of cooperation between engineering design sciences and psychology in Germany. These empirical studies focused on observation, analysis and interpretation of design procedures, aiming at the identification of successful design strategies.

Their main goals were:

- a reliable *documentation* of observed design procedures;
- reliable and valid *identification* and *classification* of types of design procedures;
- correlation of different design procedures with
  - *design success*, described in terms of *design quality*;
  - *mental characteristics* of the individual designer;

- *educational* and *professional background characteristics*;
- *external influences* (such as working environment).

Well-established methods exist for data collection and analysis of professional experience and mental characteristics (e.g. intelligence or special imagery) of designers. The same is true for the evaluation of design quality using e.g. value analysis or the related strategy described in VDI 2225. However, although there have been a number of empirical studies into design procedures, many different and few proven methods exist for valid observation, documentation, analysis and interpretation of the strategies and procedures of designers. This paper focuses on methods for the analysis of design procedures and their link with design quality. The objective is to contribute to a more systematic approach for analysing design activity.

3 Observation and Documentation of Design Strategies

To identify different design strategies one of the following approaches can be used.

1. The **hypothesis-driven** approach starts from a hypothetically deduced set of design strategies and categorizes the observed strategies according to the hypothetical set.
2. The **data-driven** approach starts from empirically identified, specific design procedures and tries to categorize these with respect to their procedural characteristics. Next the quality of the results for each group of strategies is assessed and statistically compared to find out whether significant relationships between types of strategies and results exist.

In both cases a pre-definition of *basic design operations* is needed. In addition, the hypothesis-driven approach usually includes a pre-definition of an appropriate *structure* of these operations. Observation and documentation of the process can then be carried out by recording the *transitions* between basic operations. Using suitable empirical methods, not only the *actually realised* design strategy, but also the strategies which were *intended* and anticipatively reported by the participants, and the *retrospectively reported* (*recapitulated*) strategies can be analysed. Appropriate methods for observation of actual procedures are e.g. video observation, photo observation, protocol analysis, thinking aloud techniques, computer-based protocols (an overview is given in [3], p.241). The intended and the retrospectively recognised design strategies can be examined by card-sorting-techniques, interviews, questionnaires, maps as visualisation of the design procedure, etc..

For further data-processing the visualisation using *process charts or matrices* and *transition matrices* has been established.

In process charts and matrices a postulated order of basic operations is entered along the vertical axis, and time or time intervals are entered along the horizontal axis (or vice versa). A design procedure according to a postulated type usually follows the main diagonal of the chart or matrix.

In transition matrices ([5], pp.56-58) the postulated order of basic operations is entered along both axes. The cells of the matrix contain the number of times a transition from a specific operation on the horizontal axis to one on the vertical axis has taken place. A design procedure according to a postulated type follows a line *one step above* the main diagonal.

4 Analysis and Interpretation of Design Strategies

Even though many empirical studies aim at identifying successful and less successful design strategies, further analysis and interpretation of the data based on these matrices is carried out in many different ways, reducing comparability and reliability of the results. To avoid these problems, a systematisation of the analysis procedure is proposed. In general, the following approaches for analysing process and transition matrices can be observed:

- *absolute analysis* of the matrix structure;
- *relative analysis* of distances by processing number and magnitude of transitions using descriptive statistics;
- *quantification* of deviations from postulated procedures using numerical indicators;
- *qualitative-visual analysis* of the absolute and relative matrix structure.

The results of these fundamental approaches are of different *breadth, depth*, *precision* and *reproducibility*. From this, one can conclude that: each method has its *specific area of applicability*, the *prerequisites* for the application of each method have to be identified and considered to ensure validity of the results, and a suitable *combination of methods* should be employed to cover the research objectives.

5 A Systematic Approach

Based on the above, a systematic approach to the planning of empirical studies into design procedures is proposed, containing expected *basic design operations*, a hypothesis-driven *determination of design strategies*, a set of *observation methods* for capturing design procedures and a set of *methods for analysis and interpretation* of design procedures. The earlier mentioned empirical study is used as an example [1].

5.1 Expected Basic Design Operations

Following established design methodologies and results of other empirical studies, a set of expected basic operations in conceptual design and early embodiment design stages can be formulated.

Table 1. Basic design operations in the conceptual and embodiment design stages (after [7], p. 140)

conceptual design	**hypothetical basic operations**
information	• identify task and requirements
definition	• abstract to identify the essential problems • establish function structures
creation	• search for working principles • combine working principles into working structures • outline principle solutions (e.g. sketches) • select suitable combinations/ principle solutions • firm up into principle solution variants
evaluation/ decision	• evaluate variants against technical and economic criteria • definition of principle solution (concept)

embodiment design	hypothetical basic operations
preliminary layout	• comprehend task and requirements • comprehend concept/ principle solution • identify embodiment-determining requirements • clarify spatial constraints • identify embodiment-determining main function carriers • develop preliminary layouts and form designs for main function carriers • select suitable preliminary layouts • develop preliminary layouts and form designs for remaining main function carriers
detailed layout	• search for solutions to auxiliary functions • develop detailed layouts and form designs for main function carriers • develop detailed layouts and form designs for the auxiliary function carriers and complete overall layout • evaluate against technical and economical criteria
completion and checks	• optimise and complete form designs • check for errors and disturbing factors • complete overall layout • definition of overall embodiment design

Not all of these operations are necessarily expected to be observed in every design process nor are these expected to be carried out in the postulated order. In literature slightly different sets of basic design operations might have been proposed (an overview can be found in [3], p.240), but generally speaking the set given in Table 1 can be considered as comprehensive and typical for those used in design studies.

5.2 A Hypothesis-driven Determination of Design Strategies According to Cognitive Psychology and Action Regulation Theory

The mental characteristics of engineering designers are usually described in terms of design thinking, or more precisely design problem solving. On the one hand, this description is helpful, because important characteristics of the involved thinking process are stressed. These are for instance:

- In contrast to generic laboratory tasks that do not require specific knowledge, design thinking deals with knowledge-rich tasks.

- Design thinking involves processing of a chain of effects: the designer has to generate spatial objects, that implement specific functions, and that, finally, will have intended effects.

- Design thinking has to cope with highly complex requirements, which often cannot be accomplished in an optimal manner: The designer ideally has to imagine all possible solutions as an exhaustive combination of their characteristics in order to select the optimal one. However, this is impossible since human mental capacity is strictly limited.

On the other hand, a description of engineering design in terms of design problem solving is doubtful. Firstly, it limits the focus to cognitive problem solving, neglecting the typically dynamic nature of design problems, even though the rather static initial conception of problem solving in Cognitive Psychology has changed much since its inception in the early 70s. Furthermore, the decisive aspect of knowledge application is overlooked, the role of mental capacity (working memory) and “cognitive cost effectiveness” [9] is not discussed, and the external kinds of processing like sketching, writing, impromptu-modelling, debating or gesturing are not considered either. Secondly, the approach of design problem solving reduces the complex and context-dependent activity of engineering design to the level of isolated mental processes: even the sum of all mental processes involved may not explain the characteristics of a successful goal-oriental engineering design activity.

Our proposal is to describe engineering design in terms of Action Regulation Theory as a goal-oriented mental working activity [6]. Following this approach, four types of design procedures can be developed as hypotheses: hierarchically phase-oriented, hierarchically object-oriented (or subproblem-oriented), opportunistic and associative.

Following proposals of methodologies such as e.g. the German VDI 2221, a procedure can be characterised as organised sequentially and hierarchically at the same time. A hierarchical organisation involves the systematic decomposition of the overall task into partial goals, that can be decomposed into smaller and smaller subgoals. These subgoals are accomplished sequentially following a predetermined plan. The process thus involves a combination of hierarchical top-down mental decomposition and sequential goal accomplishment. An overall task can be decomposed systematically in terms of the necessary design activities (e.g. clarification of the task, development of solution principles, selection of an optimal method) or in terms of systems and sub-systems to be designed. The type of decomposition determines the first two types of design procedures. The other two types follow other approaches.

1. A design activity is executed for all subsystems before the next activity takes place, which is again executed for all subsystems, and so on. This kind of procedure can be called *hierarchically phase-oriented* (following e.g.[5] p.89, see **A** in Figure 4).
2. All design activities are executed for one sub-system before they are executed for the next sub-system, and so on. This kind of procedure is called *hierarchically object-oriented* or *hierarchically sub-problem-oriented* ([5], p.89, see **B** in Figure 4).
3. The third procedure is a knowledge-driven *opportunistic and associative* procedure (see **C** in Figure 4). Instead of starting with a complete and systematic 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. Next, the designer may improve the preliminary decomposition with the help of the solution he just realised. This procedure shows a strong similarity to the TEA (task-episode-accumulation) model ([8]). This is a mixture of a top-down, more or less systematic 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. Since engineering design normally consists of knowledge-driven and reasoning-driven steps, it seems likely that this procedure can be identified.
4. From the point of view of action regulation, a trial and error-like *muddling through* procedure may be identified (see **D** in Figure 4), which involves a more or less unsystematic trying to cope with different parts of the system and different design activities.

5.3 Observation Methods for Capturing Design Procedures

For the observation of design procedures of a large number of participants (N=81), with up to 35 participants in one session, working parallel on individual tasks, we used photo-documentation, the time-dependent use of differently coloured pencils and self-protocols.

Data on the intended and the recapitulated procedures was collected by means of questionnaires and card-sorting. The data was transferred to process matrices (Figure 1) by a team of three design experts. In this way, not only changes in basic design operations could be identified but also potentially associated changes between sub-systems (e.g. between a gear and a clutch, visualised by different hatching in Figure 1). For observation in the currently running second phase of the study (single test-design with only one participant in each test) the method of participant observation is used, supported by a software tool for real-time data-capture. The software tool automatically converts the data into process charts.

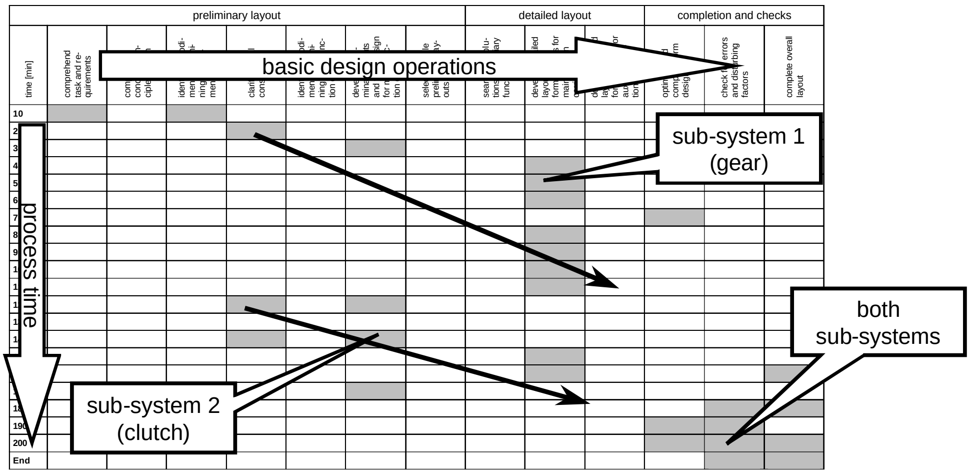

Figure 1. Example of a process matrix

For further processing, the process matrices were transferred into transition matrices. These allow the joint visualisation of *number* and *size* of observed transitions between two design operations (see the example C4(row)⇒D2(column) in Figure 2). Transition matrices are of particular advantage for visualisation of long processes because, in contrast to process matrixes, there is no expending time-axis.

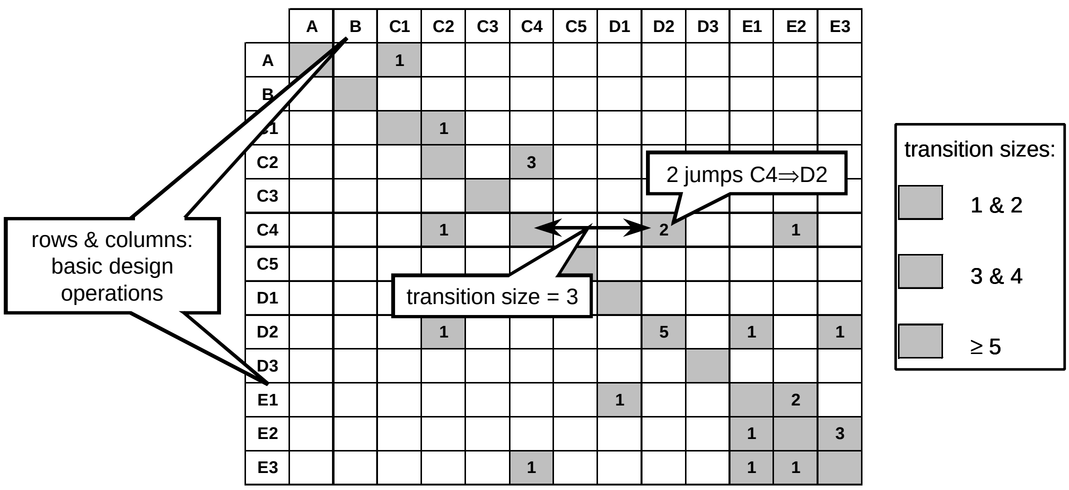

Figure 2. Example of a Transition matrix (set up after [5])

These methods give very good first advice for the interpretation of the recorded data and are easy to support by software. However, for the valid identification of different design procedures according to the mentioned hypotheses, further analysis of the data is needed.

5.4 Methods for Analysis and Interpretation of Design Procedures

For further processing of process and transition matrices, first a frequency analysis based on the observed transition sizes was carried out. The number of 'hits' within cells representing a predefined class of transition-sizes (visualised as cells with equal hatching in Figure 2) were summed and plotted in a bar chart. This provided a very good first indication of different design procedures (compare e.g. participant 61 to 85 in Figure 3).

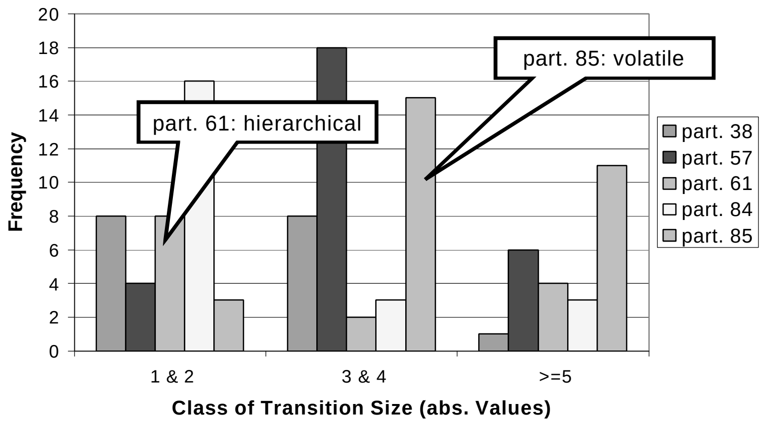

Figure 3. Example of a bar chart visualising the different frequencies of transition-sizes of 5 participants

To validate the hypothetically determined design procedures, a distinction was made between activity transitions that, at the same time, involved a sub-system transition, and activity transitions that did not involve a sub-system transition. The mean values of the transition sizes in both cases were determined and entered into a portfolio diagram (Figure 4) along different axes. This allowed a valid distinction of the procedures in the indicated sectors (A-D).

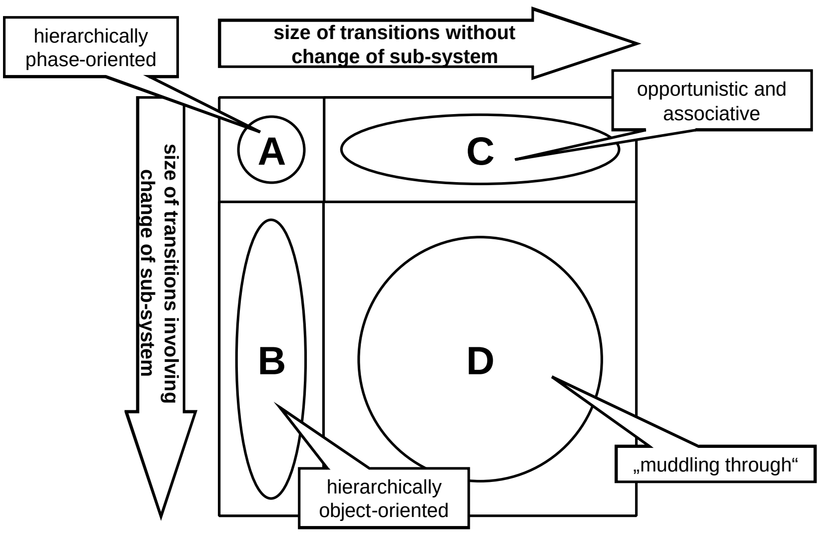

Figure 4. Portfolio-diagram identifying four different design procedures

6 Conclusion

This paper is intended as a contribution to the systematisation of empirical design research. Its main focus is on comparability and reproducibility to enable validation of methods and results. Aims and objectives of empirical studies into design procedures, methods for data capture, analysis and interpretation were discussed. As a result an approach for systematic conceptualisation of empirical studies into design procedures is proposed (documented in detail in [2]) which is to be considered as an element of a "general design research methodology"[4].

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