Design Thinking – Possible Ways to Successful Solutions in Product Development

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Abstract

Engineering design is analysed in terms of design problem-solving. Engineering designers of differing productivity hardly differ in mental abilities, as measured by intelligence testing, but in their strategies concerning the analysis of requirements and of the problem, in the search for general principles that solve the relevant problem, and in the procedures that develop specific solutions. Experimental and interview results stress that the interrelationship between thinking and sketching, as well as other kinds of early low-cost prototyping, are of crucial importance for the efficiency of the problem-solving procedure and the result. Possibilities of assisting design problem-solving and of improving the training of designers are discussed.

1. Introduction: Engineering Design as Thinking and Problem-solving

Engineering design – like other designing activities, for example the design of technological processes or software design – is a working activity with a decisive impact on two key problems of economic development. The first issue is the design of innovative products to gain access to new markets; the second concerns the competitive prices of these products. Thus, engineering design will have a high impact on competition within regions and between firms.

What are the characteristics of 'engineering design'?

According to Steuer [1], engineering design means 'thinking ahead creatively and completely in order to create a technical object fitting with the requirements of the historically determined level of technological trends and the development of all documents necessary for its physical implementation. It consists of designing and shaping'. This definition concentrates on two types of design tasks only: on the design of completely new objects and on the adaptation of given solutions to new requirements. It more or less neglects tasks that require the recombination of already elaborated modules. This paper will confine itself to tasks covered by the cited definition.

According to the definition, engineering design is a thinking activity, more precisely the most complicated type of the manifold types of thinking and problem-solving. It just does not imply reasoning on an already given issue, but thinking ahead in the sense of developing the mental model of a future object that has never existed so far. Furthermore, this thinking ahead should be creative because the future object should have useful new parameters.

This 'design problem-solving' process [2] contains some important phases. The main ones are:

1. identification and clarification of the problem,
2. development of a frame conception of solutions,
3. design of the favoured solution, and
4. working out the details [3].

The main point is that the least observable and least formalisable 'early phases' of task identification and the development of a frame conception of solutions will have the highest impact on innovativeness and on manufacturing costs. Ehrlenspiel [4] illustrated this decisive function for the possibility of influencing costs. This influence will be much higher within the early phases of design problem-solving than in later ones, but is only vaguely calculable. To stress the point: a reliable calculation of the costs of a design result only becomes feasible when it is too late to do anything about them.

Consequently, in its early phases, engineering means problem-solving with high uncertainty concerning its results. On the one hand this uncertainty offers a challenge to proceed to innovative solutions, on the other one, however, it also implies the risk of detours and failures. Thus, uncertainty may challenge or worry the designer and in the final analysis simply inhibit a creative procedure. Therefore engineering design is design problem-solving with an internal contradiction between challenging options and stressing risks. At this point the question arises whether possibilities exist to support design problem-solving. Working activities need strategies that offer information – what options should be used and what detours should be avoided. Such strategies or technologies may support manufacturing as well as information processing activities. There are no convincing arguments why it should be not feasible to develop a technology of efficient design problem-solving. First modules are offered and are successfully applied in design education and daily work. Examples are guideline 2221 of the Verein Deutscher Ingenieure [5] offering a strategy of engineering design, or the textbooks on design strategies - in Germany for example Hansen [6] or Ehrlenspiel [4], both integrated into the frame approach of Pahl & Beitz [3].

What might be contributed by Psychology to the further development of supporting strategies or even of a methodology of engineering design?

First of all, highly and less efficient designers may not be distinguished significantly in terms of their intelligence as measured by traditional tests [7]. Spatial imagination, too, will contribute only marginally to an explanation of excellent versus less convincing solutions. Even job experience does not explain the quality of solutions sufficiently.

A more promising approach offers the analysis of working strategies of designers. Before, however, discussing these mental working strategies it is important to bring into mind a few essential characteristics of thinking within engineering design. Thinking strategies should not be misinterpreted. Thinking may follow logic or other systematic rule systems in some cases, but in others it might not. It may apply rational and abstract concepts, but can also be based on pictorial imagination. The thinking process may be consciously controlled and verbalisable, however more often an unconscious, implicit or tacit processing takes place which in some situations may converge into sudden conscious insight. Finally, thinking as design problem-solving mostly combines the development of actual new solutions with an activation of conscious or tacit knowledge of already known ones.

In order to support and optimise engineering design processes, design problems of different requirements must be studied and compared. Unfortunately, however, an agreed and valid procedure to analyse and rank the requirements and, thus, the difficulties of engineering design problems is still lacking. Therefore we have tried to develop a first draft of a requirement analysis.

2. Requirements of Engineering Design Problems

Problems are characterised by subjective and objective features. Subjective features refer to the individual mental representation of a problem including individual ability, experience and the knowledge of a problem solver about the field and about possible operations. This is often described as 'problem space' [29]. The objective features refer to characteristics of the task structure that are independent of the concrete problem solver. A general and formal classification for engineering design problems should focus on this task structure. There are several existing taxonomies for engineering design problems [8–11]. Based on these ideas we propose the following criteria and operationalisations [29, 30].

1. **Multiplicity of goals** (number of goals, number of conflicting goals and strength of conflicts between the goals)
2. **Complexity** (number of subfunctions, number of interactions between subfunctions, strength of the interactions)
3. **Transparency** (information about the situation, information about the method of solution, information about the solution aimed at)
4. **Degrees of freedom** (number of possible variants of solution, number of possible ways of obtaining solution)
5. **Dynamics** (changeability of the situation, predictability of the consequences of the problem solver's action and desicions, influences from outside)
6. **Necessary knowledge** (specific knowledge about facts, specific knowledge about methods, general problem-solving strategies)

These criteria are differently weighted by different design experts [22, 30–31]. They attribute high importance to the multiplicity of goals and problem complexity, medium importance to transparency, degrees of freedom and necessary knowledge, and low importance to the dynamics. There is a satisfying reliability and concordance of the averaged expert rating judgements for nearly all criteria (Table 1).

Table 1: Reliability and concordance of the criteria (*N* = 58 experienced designers).

Criterion	Reliability (Cronbach´s Alpha)	Concordance (Kendall´s τ)
multiplicity of goals	.85	–
complexity	.81	.59$^{(*)}$
transparency	.73	.48
degrees of freedom	.78	.71*
dynamics	.77	.77*
necessary knowledge	.54	.66*

** ... p< 0.05; (*) ... p < 0.1*

Thus, based on this requirement assessment an overall problem difficulty may be calculated by a weighted sum. Moreover, the individual requirement dimensions may be represented as a profile of task difficulty. Figure 1 shows the different design tasks for two examples.

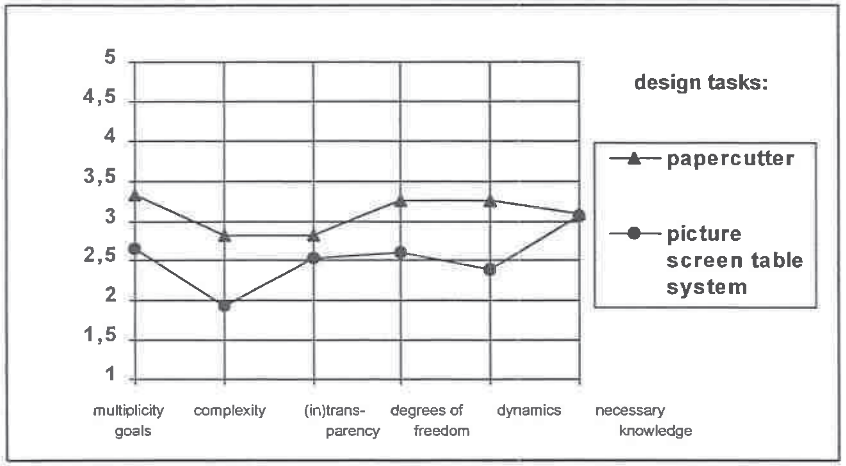

Figure 1: Profile of task difficulty.

These first results encourage further research in this topic. A valid checklist for requirement analysis might be highly useful in several directions. From an theoretical point of view it would be an essential instrument for problem-solving design research. From a more practical point of view, an instrument for requirement analysis might help with both, engineering design education and the organisation of engineering design tasks in industry. In the first case the instrument might ease the difficulty of sequencing learning tasks, in the second it might offer a rough estimate of the necessary working time as a prerequisite of planning.

3. Characteristics of Successful Strategies in Engineering Design

The following review draws on unpublished results of our Dresden research group and on the literature [12–19, 22, 30, 31]. Successful procedures are based on characteristics of the development and implementation of intentions on the one side (the intention aspect), and on the procedures and tools applied in implementation on the other side (implementation aspect).

Seen from the *intention* side, successful strategies are goal-directed and planning procedures. The task, internalised as the intention or goal of the design process, is clarified extraordinarily thoroughly, the individual goals are integrated into a plan but nevertheless they are dealt with in a flexible manner.

Seen from the *implementation* point of view, in successful strategies first of all a couple of different solution principles are developed and compared, before the 'search space' is efficiently focused on the one most promising version. Moreover, problem-solving and knowledge application are efficiently combined.

Three main characteristics of successful procedures should be stressed in detail:

a) Clarification of the task

The often discussed 'first idea' actually does not have an important role within the procedures of either experts or novices. Rather they first of all scan their knowledge in order to start an analogous reasoning [16]. The procedures of successful experts differ from those of less successful novices with respect to a refined clarification of the task, a subtle definition of goals concerning subfunctions and a thorough extraction of those aspects that are important for product functions – not simply for its shape.

Consequently, going into detail, the characteristics of a successful design procedure are:

- a thorough clarification of the task
- concentration on components that determine the functions of the objects
- an exhaustive analysis of the main functions
- the weighted integration of the goal characteristics to be implemented
- the written or sketched fixation of the solution principles of the goal
- a goal-oriented but nevertheless flexible method of processing.

In an experimental analysis, a significant relationship was found between the number of goal characteristics analysed and the quality of the resulting design solution [16].

A second group of characteristics of successful procedures concerns

b) The type of search for a solution principle

Engineering design is more than design problem-solving. In most cases there is no well-defined problem given, which just needs to be solved. Instead, first of all the key problem itself must be defined. Therefore several variants of a solution principle need to be developed, then the most promising of these needs to be selected in order, finally, to solve just that problem. However, this procedure is not only rule-governed deduction but also creative induction.

Going into some detail again, the characteristics of a successful procedure here are [9, 13, 15, 20–22]:

- A procedure generating new solutions instead of only modifying already given ones.
- Conceiving a few different principal solutions before starting to work out one selected solution principle. This so-called *divergent* search phase in successful design must be followed by
- A *convergent* restriction of the variety of solution principles (the 'search space') on as few variants – which are worked out – as possible.
- A well-scheduled phase of detailed design, corresponding with the proposals of design methodologies: to develop and logically follow the ordered subgoals [23]. However, in spite of this goal-directed processing, the expert procedures are not obviously straightforward. There are anticipations of later steps and regressions to already processed ones, although less frequently than within less successful procedures.

The third group of characteristics of successful procedures concerns

c) The evaluation of the solution procedures

In successful procedures, more feedback is processed which guides further operations. In detail:

- The process and its outcome are more often evaluated in terms of goal characteristics, and
- The evaluation is made for both levels, the global solution principle and the detailed solution steps worked out.

This macro-procedure of engineering design discussed so far may be broken down into two components of problem-solving, the development of mental representations and the operations on these representations. What about the differences between design procedures in terms of these components?

4. Characteristics of Solution-supporting Mental Representations

Problem-solving requires the development of correct and complete mental representations as the materials of internal processing operations. The mental representations are the search space; no solution will be better than the search space will allow: the final solution will depend on whether the relevant solution possibilities were represented or stored mentally. Consequently the designer ideally should imagine all relevant solutions through an exhaustive combination of their features in order to select an optimal feature pattern from all possible ones. Just this, however, is often impossible because of the limitations of human mental capacity, often labelled 'capacity of consciousness' or 'working memory'. Thus the designer is forced to concentrate on a selection of features only. However, he will restrict not because he could not imagine further feature patterns, but because he cannot hold all of them within consciousness. Nevertheless the selection should contain just the optimal solutions of design. Thus the critical issue turns out to be: designers should have in mind the optimal feature patterns of a required solution which, however, in most cases they cannot know, since they should have been selected from the total of possible combinations which they cannot hold in consciousness.

Obviously the bottleneck of creative design in the first place is not the variety of designer's solution ideas but the limitation of working memory. Actually we could show experimentally with simulated computer-based design tasks that the lower the working memory span of a subject, the more superfluous steps are considered, the more inefficient solutions paths are tested repeatedly, and the higher the time consumption will be.

Thus, a possible way to support design problem-solving is to relieve working memory load. Just this was one of the above mentioned characteristics of successful procedures: experts tend to fix their ideas by writing and sketching. A labelled sketch as an external store offers a way out of the conflict discussed.

5. Solution-supporting Design Procedures: Designing as Interaction of Internal and External Processing

Now consider a designer who has developed a search space in mind, and who must operate on its representations. He should compare the characteristics of the solution variants, recombine characteristics, introduce new characteristics and reject irrelevant ones. Here the procedures of human beings strictly differ from those of computers. Designers in most cases will not start from the details and proceed to a complete solution. Rather they will start from a vague impression of a complete solution and proceed to details. To quote a description by Bach, the designer frequently will start 'not from individual elements of a solution, but from a holistic solution. It will contain already all details which will be unfolded within the process of design. Thus designing is a stepwise decomposition and clarification of partial functions ... It is a holistic-analytical procedure ... The designer creatively works on two levels: On the one hand he more or less unconsciously applies abstract, complete solution structures, on the other hand he consciously sketches specific combinations of elements ...' [24, p. 4].

This human design procedure needs external, sensorimotor support because human beings are 'thinking with their hands'. There is an analogy with 'the gradual development of an idea while speaking' [25]: often solution ideas are developed gradually within the process of sketching by hand. Solution ideas are fixed as an abstracting sketch of the solution principle and are specified afterwards within feedback-circles of thinking, sketching and critical inspection of the refined sketch. Thus, quoting Görners observations '... the sketch not only offers the results of the designer's thinking processes but mainly serves him as a working means' [16, p. 240]. In an interview study he analysed 74 experienced designers. One of the questions was, whether they use – in order to develop a solution principle – 'mainly thinking about it or mainly sketching'. 69.3 % of the designers were 'mainly sketching', 3.8% 'mainly thinking' and 26.9% reported a balanced combination of thinking and sketching (Figure 2).

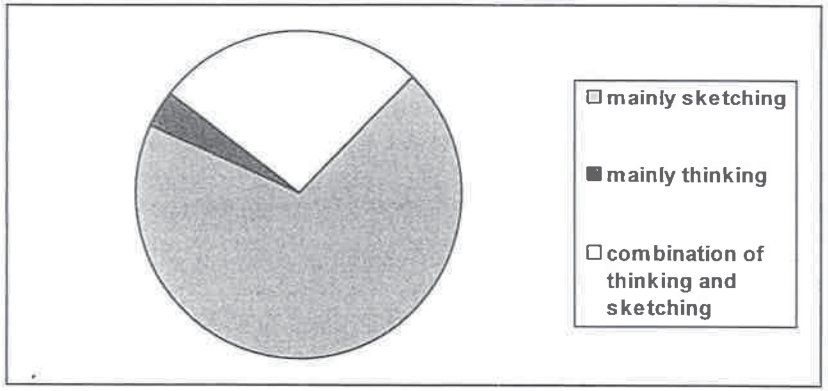

Figure 2: Interview study (*N* = 74 experienced designers).

A further question dealt with the reasons for sketching. The respondents here could apply more than one category: 61.5 % of them applied sketches in order to clarify an idea, 44.4% stressed the role of a sketch as memory aid, and 30.8% stressed the role of communication (Figure 3).

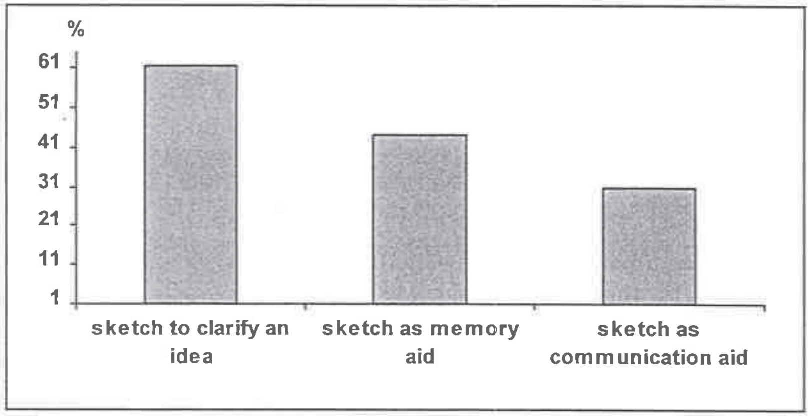

Figure 3: Interview study (*N* = 74 experienced designers).

To overcome the shortcomings of an interview study we carried out the following experiment. Two matched groups of students by means of a computer program dealt with three design tasks of different complexity. One group was asked to sketch their ideas first of all, the other was not. With the most complex task a significant difference was revealed. In the case of previous sketching, the number of operations in task accomplishment was lower, fewer operations needed to be corrected, the perceived difficulty of the task was lower, and – in spite of the additional sketching phase – the total working time was lower, each in comparison with the group not using sketching [26].

In addition to sketching, a couple of still more 'materialising' kinds of operations may support design problem-solving. Even in the area of CAD and digital prototyping, many simple physical prototypes and models are applied. Designers use pencils, rods, paper, cardboard, wire or plasticine models or elements of building kits, in addition to the more sophisticated computation, CAD or stereolithographic models. An interview study with a further 40 experienced engineering designers revealed the following main functions of the concrete simple prototypes: they serve as a means of problem analysis, an aid to create new ideas, an instrument of evaluation, especially of functions, a means of storage relieving working memory, and a communication support [27].

Consequently – as was shown recently also by Ehrlenspiel, Bernard & Günther [21] – the simple concrete prototypes are very useful, especially within the early phases of design problem-finding and solving. Therefore the application of this 'early low-cost rapid prototyping' should be facilitated along with the application of the more extensive high-tech types of modelling and prototyping, and it should be integrated into design education.

6. Design Procedures Continued: Knowledge-based Opportunistic Solution Procedures

Design problem-solving involves more than just thinking. To a great extent it is a knowledge-based development of solutions. Thus, it integrates the reactivation of already known solutions and the development of actual new ones.

Through this integration the design process becomes an opportunistic procedure: it does not just proceed systematically towards the goal without any jumping between subfunctions or modules. Rather the procedure will start at some isolated islands of given knowledge and try to rearrange and to combine them stepwise by thinking. For that reason, backward jumps to already processed steps and forward ones to future steps of processing are inevitable. A systematic goal-directed procedure will only become possible when the problem analysis has found a suitable way of breaking down the total problem into subproblems. Thus, empirical results contradict the assumption of a systematic problem-solving procedure, as was assumed for instance with the waterfall metaphor of software design [28]. Instead of a systematic procedure from task clarification, searching for solution principles, and detailed development of a solution, another procedure prevails. It is based on the detection of solution-relevant knowledge while working. This opportunistic procedure shows the following characteristics:

- It switches seemingly irregular between mental and external (sketching, modelling) processing of subproblems.
- It accomplishes no complete clarification and decomposition of the total task before starting the design. Thus, its initial problem definition is global and incomplete.
- It switches between subproblems and levels of problem description, caused by the experience-based identification of applicable knowledge.
- The transferred knowledge leads to redefinitions of the problem and to changes of developed action programmes (plans).

Again an important consequence arises: the broadly announced methodologies of design may support engineering design only if they do not force a strictly systematic procedure following theoretically optimal phases. Rather they should offer optional guidelines which in particular will not restrict the naturally opportunistic initial steps of design problem identification and solving.

7. General Consequences

The initial phases of design problem-solving are task clarification with the identification and decomposition of the problem and the selection or development of a solution principle. These phases are of essential impact for the result and its costs. A couple of teachable procedures may be recommended to improve engineering design education concerning these phases.

Because design combines knowledge activation with problem-solving, the initial phases cannot proceed systematically towards a final result until the problem is clarified and decomposed into its subproblems. Therefore a useful design methodology should offer flexible, heuristic guidelines instead of strict algorithmic rules.

The bottleneck of creative design is less a deficit of ideas, but rather a limitation of conscious information processing, measurable by the working memory span. This limitation can be diminished by sketching and the development of external models.

Moreover, sketching and modelling will support the development, selection and correction of ideas. Therefore only in the initial phases of design should these aids be applied, and their application should be supported.

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