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External Support of Problem Analysis in Design Problem Solving

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Abstract. *Design is described as creative design problem solving. The first step of the design process is to identify and analyze the design problem. This step has an important influence on the creation of an effective design solution. In two experiments, we tested the benefits that sketching provides during the analysis process in design problem solving. In particular, this paper focuses on the design process, the act of sketching, the sketch itself, and the final product. In prior studies, the process of sketching has been shown to enhance the construction of a mental representation, and thus the sketch has improved the analysis of the problem. The memory supporting effect of sketches is verified in the second experiment discussed in this paper. Finally, this paper also discusses the support possibilities the sketch offers for the early stages of the design process.*

Keywords: Design problem solving; External aids; Problem analysis

1. Introduction

The design process in its essential components is described as a complex and fastidious mental activity. Design is not only inspecting given circumstances and reproducing already well known solutions, but it is also thinking about new approaches and creating a non-existent object – it is design problem solving (Thomas and Caroll 1979; Rowe 1987; Hegarty 1991; Smith and Browne 1993; Radcliffe 1998). Generally described, the phases of the design process are differentiated as (1) task clarification, (2) conceptual design (solution definition in principle), (3) embodiment design (formative solution definition), and (4) detail design (Pahl and Beitz 1997).

The paper deals with the early stages of task clarification and conceptual design because of their determinant influence on results and costs of design (Ehrlenspiel 1995). We investigate the efficient use of external aids like sketches and models as a potential of product development, where one can decrease development costs, reduce development time, and improve the quality of the final product.

Prior studies have demonstrated that using such external aids lead to a significantly more successful problem handling, expressed in a higher solution quality, fewer steps to achieve the solution, and a lower level of the experienced task difficulty. In this context, the functions of different external aids are described as supporting problem analysis, solution development, solution evaluation, memory and communication (Sachse and Hacker 1997; Sachse et al. 1999).

However, from these prior studies, it is not possible to determine the benefit ratio of the process (sketching or modeling) to the product (sketch or model). Therefore, we want to analyze the supportive effect of sketches, models and prototypes. We think that prior studies have adequately confirmed that the process of sketching or modeling itself has a supportive effect on both the problem analysis and developing the mental representation of the problem and its conditions.

2. Problem Solving and Design

A problem exists when a person perceives characteristics of the task environment, represents them in an internal problem space, and recognizes that this internal representation contains one or more unsatisfactory gaps. The problem solver experiences a barrier between the well known present state and the desired goal (Lüer and Spada 1990). The design process can be understood as a problem solving process, because often an experience-based problem handling approach is not possible. 'Design problems' are usually difficult, ill-defined problems, which require the activation and organization of a large amount of various types of knowledge to solve them

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(Dörner 1976; Pahl 1994; Kintsch and Ericsson 1996; Sachse and Hacker 1997; Hacker 1998). If a task is unfamiliar and the requirements are difficult and complex, a clear separation between understanding the problem and subsequent development of solutions is expected. Problem analysis, problem decomposition in a sequence of part-problems, and understanding of interaction among the part-problems are prerequisites for successful design problem solving (in terms of both performance and result). Skipping over or insufficient handling of the problem analysis entails a high risk of error and result uncertainty (Hayes and Simon 1974; Brown and Chandrasekaran 1989; Ellis and Hunt 1993; Ehrlenspiel 1995; Kintsch and Ericsson 1996; Hacker 1998). Görner (1994) demonstrated a significant coherence between a detailed problem analysis and a high solution quality.

The problem space as a subjective representation of the task environment contains the problem solvers knowledge of the problem, the amount of available operators, and the picture of the problem itself (Klix 1971; Newell and Simon 1972; Anderson 1988; Kluwe 1990). If a cognitive requirement based on externally given information is to be coped with, an appropriate representation has to be constructed or modified, respectively forming the base of the requirement coping. Thus, two components of the process are characterized: the process of constructing and transforming a mental representation and the process of using this mental representation for coping with the requirement (Sommerfeld et al. 1996).

A successful performance depends upon the construction of mental solution possibilities in the problem space and the accuracy of these representations for the solution. Thus, the representation of the task environment in the problem space is a key for a successful solution (Dörner 1976; Brown and Chandrasekaran 1989; Tergan 1989; Ellis and Hunt 1993; Hacker 1998; Sachse 1999).

Studies about quality and functions of mental representations in action regulation have shown performance improvements and a decrease of the experienced task difficulty due to the development of mental representations. The construction of an action-regulating mental model reduced the required time, the error rate, and the expeienced difficulty (Hacker and Clauss 1976; Matern 1976; Hacker and Matern 1979).

The more the mental resources are loaded, the less successful the problem solving will be, since the problem solver works against the load of 'working memory' by declarative and procedural simplification. There is a danger that relevant aspects are faded out or missed due to declarative simplification, the unintentional loss of information from working memory based on overloading and interfering with the processing, activating and remembering processes. Due to these simplifications, a less efficient and less successful problem solving method, as well as the appearance of 'illegal' operations during the problem solving, can be observed (Egan and Greeno 1974; Dörner 1974, 1989; Hussy 1984; Anderson and Jeffries 1985; Klauer 1993).

3. Design Problem Solving Support by Sketches and Models

Designing is a purposeful activity. It includes both complex internal steps (thinking, evaluation, decision) and external steps (writing, drawing, speaking).

External aids (e.g. sketches and physical models) can contribute to a more detailed problem analysis. With their help, information can be stored externally, and therefore information activating processes can be reduced. By representing the information externally, an overload of mental resources and an interference of processing processes is prevented or restricted, respectively. Sketches and models take over the function of external stores (Muthig and Schönpflug 1981; Schönpflug 1986; Sachse et al. 1999).

Prior investigations with experienced and CAD-using designers show that in addition to sketches, simple stick-, wire- or plasticine-models, as well as the fastidious calculation-, CAD, FEM-, or VR-models, are used as external aids for mental elements in the problem-solving process (Sachse and Leinert 1996).

Carroll et al. (1980) see the supportive effect of graphic representation aids as a way to make the information more accessible. Beyond a simple memory-relieving effect, sketches and models support problem analysis by helping to construct internal problem representations. On the one hand, producing a sketch or model contributes to the visualization of solution concepts; on the other hand, it entails the differentiation, control and correction of these concepts. Thus, external representations are important aids for a well-organized thinking process (Mandl and Spada 1988; Ullman et al. 1990; Goel 1995; Sachse and Hacker 1997; Purcell and Gero 1998; McGown et al. 1998; Hacker 1998).

Furthermore, it can be assumed that in addition to the use of a sketch or model, the process of sketching or modeling itself is supportive for designing. In his 'Interiorization/Exteriorization' concept of mental processing, Galperin (1966) theoretically showed that human thinking and processing always unites 'internal' and 'external' parts. During the design process, internalization (interiorization) and externalization (exteriorization) frequently change together. Similar to Heinrich von Kleist's statment about a gradual production of thought when talking, frequently, a gradual production of the solution takes place while sketching and modeling. The design sketch reflects not only the result of the thinking of the designer, but primarily serves the designer as a medium for soluton development (Görner 1994).

The change between internl and external working can entail a relief of working memory and, at the same time, a decrease in the experienced stress of the problem solver's mental resources. Externalization is not only the fixation of internal produced solutions, but also the production of solutions (Ullman et al. 1990; Klauer 1993; Hacker 1998, Radcliffe 1998; Sachse et al. 1999).

4. Experimental Results Regarding Support by Sketching

The topic of this study was the influence of sketching on the representation of the initial states during problem analysis. We were interested in the subsequent questions (Leinert 1997; Römer 1998):

1. Does sketching in addition to a mental problem analysis support the construction of a mental problem representation, so that compared with an exclusively mental problem analysis, more facts and relations can be recognized and reported?

   After the problem analysis, a questionnaire was given regarding the facts and relations of the initial conditions of mechanical-physical systems with different stages of complexity to understand the mental problem representation at this stage of the process. (*Experiment 1*)
2. Does sketching, in addition to a mental problem analysis, support the construction of a mental problem representation even when a longer interruption occurs between the construction phase and the operation phase, as well as when the sketch is not available as an external storage? (*Experiment 2*)
3. Furthermore, in *Experiment 2*, an additional experimental condition was applied. Here the participants could fall back on their produced sketches. It should be clarified whether the operations at the constructed representation are influenced by the possibility of a later recuorse to the produced sketch, evaluating the benefit of an external store.

4.1. Methods

A sample of 108 students of different faculties of the Dresden University of Technology had to analyze mechanical-physical systems of different complexity, so that after a certain period of time they could answer questions about facts and relations without falling back on the experimental documents presented (exception: sketching without withdrawal). The descriptions of the mechanical-physical systems used in the experiment were derived from a demonstration example developed by Larkin and Simon (1987).

Example for a system description (system 3 in Experiment 1):

The rope x goes over the fixed roller A and under the loose roller B.
The right end of the rope is connected with a carrier, and on the left end of this rope hangs weight 1.
Weight 2 hangs with a rope on the loose roller B.
The fixed roller A is connected over a rope with the carrier.
The roller A is situated on the left side, the roller B is situated on the right side.

Hegarty (1991) refers to such mechanical systems as possible starting points for simple design problems, e.g. if the appropriate configuration of rollers and ropes for uplifting a weight is unknown.

During the analysis of these systems, the participants had to recognize the construction of the respective systems (facts) as well as the dependencies among the elements and the conditions in the whole system (relations). After the system analysis, they answered two identical sets of questions for each of the mechanical systems. Each set of questions focused on one of the facts without considering its relation to the other facts, whereas the other set of questions focused on the relations among the facts.

Example questions:

- Facts:
  How many fixed rollers are in the system?
  How many ropes are necessary for the construction?
- Relations between the facts:
  Is the system in balance if all weights have the mass of 1 pound?
  Which weights drop if the right rope fixed to the carrier is cut through?

In *Experiment 1*, in addition to the condition of system analysis, the complexity of the mechanical systems was varied (Table 2). The determination of complexity was a prerequisite for investigating the

Table 1. Complexity analysis of the mechanical-phsyical systems

	Experiment 1				Experiment 2
	Systems				
	1	2	3	4	
Number of elements	6	8	11	13	16
Steps to determine facts	9	17	24	32	40
Steps to determine relations	28	57	76	99	212

influence of complexity on the analysis and representation of the mechanical systems. In general, this determination can be made by the number of the elements and their connections (Dörner 1976). To produce a ranking of complexity of the mechanical systems in Experiments 1 and 2, and of the resulting requirement differences, the number of elements and the number of the algorithmic steps necessary for analysis and answering the questions (1 step = 1 if-then relation) were determined (according to Larkin and Simon, 1987). Table 1 displays the complexity analysis for both experiments.

Experiments 1 and 2 were both carried out in a single session. To eliminate any performance variance based on a different verbal presentation, the presentation of the mechanical systems as well as the answering of the questions, was realized in a written form.

In *Experiment 1* the participants had to analyze four mechanical systems of increasing complexity.

The analysis of the system took part under one of the following experimental conditions:

1. Presentation of the system description and system analysis with instructions to sketch (withdrawal of the description and the sketch after finished analysis).
2. Presentation of the system description and exclusively mental system analysis, i.e. no external aids available/prevention of sketching (withdrawal of the description after finished analysis).

Table 2 shows the experimental design for Experiment 1.

After the system analysis, the participants answered 23 questions about the facts and relations described, without the ability to consult any of the initial documents (as well as the sketch, if applicable). The participants could time the problem analysis and the questions answering without any time restrictions.

Table 2. Experimental design for Experiment 1

		Complexity	
		Low complexity Systems: 1 & 2	High complexity Systems: 3 & 4
Conditions of analysis	Instructions to sketch facts and their relations during analysis	$n = 30$	
	Instructions to perform an exclusively mental system analysis; i.e. no sketching	$n = 30$	

In *Experiment 2*, only one mechanical system was presented to the particpants, but as the complexity analysis shows (Table 1), this system was the most difficult to analyze and understand. The system analysis took part under one of the following experimental conditions:

1. Presentation of the system description and system analysis with instructions to sketch (withdrawal of the description and the sketch after completed analysis).
2. Presentation of the system description and system analysis with instructions to sketch (withdrawal of the description after the analysis, no withdrawal of the sketch).
3. Presentation of the system description and exclusively mental system analysis, i.e. no external aids available/prevention of sketching (withdrawal of the description after finished analysis).

Table 3 shows the experimental design of Experiment 2.

In contrast to Experiment 1, the questionnaire here was not give immediately following the system analysis, but instead, it was given after an interruption of 20 minutes. During this interruption, the faculty of spatial imagination was measured with the 3D-cube-test (Gittler 1990).

As in Experiment 1, the participants of Experiment 2 could time the problem analysis and the question answering without any time restrictions. In both experiments (Experiments 1 n 2), the time of the system analysis, The percentage of correctly reported relations, the percentage of correctly reported facts, and the subjective experienced task difficulty were measured as dependent variables. The definitions of the dependent variables are presented in Table 4.

Table 3. Experimental design for Experiment 2

	Condition of analysis	
Instructions to sketch facts and their relations during analysis (with drawal of the sketch)	Instructions to sketch facts and their relations during analysis (no withdrawal of the sketch)	Instructions for an exclusively mental system analysis, no sketching
$n = 16$	$n = 16$	$n = 16$

Table 4. Definitions of dependent variables

Dependent variable	Definition
Percentage of correctly reported facts	Number of correctly reported facts/Totality of facts
Percentage of correctly reported relations	Number of correctly reported relations/Totality of relations
Time of system analysis	Time from presentation of the system description until the self-chosen return by the participants
Subjective experienced task difficulty	Rating by the participants with a step-less scale

4.2. Results

Experiment 1
Based on a two-way analysis of variance of the factors, the *Complexity* factor influenced two variables, the *Percentage of correctly reported facts* ($F = 10.99 > F_{3;\ 53;\ 0,01} = 4.20$) and the *Percentage of correctly reported relations* ($F = 70.91 > F_{3;53;0,01} = 4.20$). Furthermore, the *Conditions of analysis* factor can be proven to have a significant influence on the dependent variables *Percentage of correctly reported facts* ($F = 5.40 > F_{1;\ 55;\ 0,05} = 4.02$) and *Percentage of correctly reported relations* ($F = 11.83 > F_{1;\ 55;\ 0,05} = 7.12$).

Between the two factors, a significant interaction existed with the variable *Percentage of correctly reported relations* ($F = 3.63 > F_{3;\ 53;\ 0,05} = 2.79$). The remaining interactions were not significant.

As expected and demonstrated in Fig. 1, the participants recognized more facts and relations correctly when they analyzed mechanical systems with a lower complexity. Participants with instructions to sketch the given facts and relations achieved a higher percentage of correctly recognized facts and relations.

Furthermore, the factors *Complexity* ($F = 37.69 > F_{3;\ 54,\ 0,01} = 4.29$) and *Conditions of analysis* ($F = 11.41 > F_{1;56;\ 0,01} = 7.12$) were found to have an influence on the variable *Subjective experienced task difficulty*. The interaction between the two factors was not significant. Sketching of facts and relations was combined with a lower level of the experienced task difficulty.

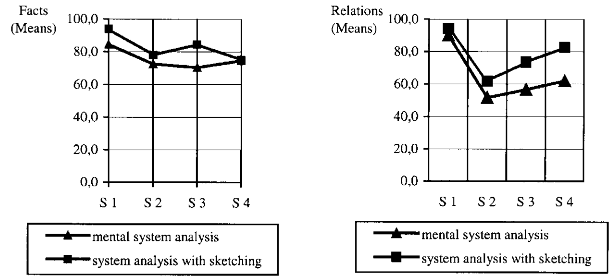

Fig. 1. *Experiment 1:* percentage of correctly reported facts and relations in different experimental conditions (S = mechanical-physical system).

Concerning the *Time of system analysis*, only one primary effect of the factor *complexity* ($F = 29.93 > F_{3;53;0,01} = 4.20$) could be proven, the effect of the *conditions of analysis* was not significant ($F = 1.31 < F_{1,55,0.05} = 4.02$), as well as the interactions between

Table 5. Means (M) and Standard Deviations (SD) of dependent variables in Experiment 1

		Systems 1 M (SD)	2 M (SD)	3 M (SD)	4 M (SD)
Percentage of correctly reported facts (in %)	A	93.9 (10.95)	77.9 (14.80)	84.4 (19.03)	75.0 (20.90)
	B	84.4 (15.87)	72.5 (17.90)	70.3 (25.41)	74.7 (19.46)
Percentage of correctly reported relations (in %)	A	94.1 (11.89)	61.8 (19.21)	73.5 (19.21)	82.5 (17.75)
	B	90.1 (11.78)	51.7 (18.43)	56.6 (21.11)	62.0 (21.37)
Time of system analysis (in minutes)	A	1.9 (1.28)	3.4 (1.83)	4.0 (1.78)	3.8 (1.76)
	B	1.9 (2.06)	2.7 (1.47)	3.6 (1.70)	3.5 (1.72)
Subjective experienced task difficulty 0 . . . not difficult at all 7 . . . very difficult	A	1.2 (1.13)	2.5 (1.52)	3.1 (1.62)	3.3 (1.52)
	B	2.2 (1.81)	3.2 (1.67)	4.7 (1.60)	4.3 (1.86)

A Instructions to sketch given facts and relations
B Condition of exclusively mental system analysis, prevention of sketching

the two factors. Thus, sketching does not prolong the time of system analysis, in spite of the greater amount of time necessary to produce them.

Table 5 shows detailed results of Experiment 1.

Experiment 2
Based on a one-way analysis of variance (ANOVA), the *Conditions of analysis* factor was found to influence two variables, the *Percentage of correctly reported facts* ($F = 7.78 > F_{2;\ 45;\ 0,01} = 5.11$) and the *Percentage of correctly reported relations* ($F = 5.67 > F_{2;\ 45;\ 0,01} = 5.11$). As shown by the comparison made using the Duncan procedure, the experimental group, who could fall back on the sketch as an external store while answering the questions, recognized more facts and relations correctly than the other two experimental groups. The group of participants for whom the sketch was withdrawn after the system analysis did not differ in either variable from the group who only mentally analyzed the mechanical system (without the aid of any external support). Figure 2 clarifies these results.

The *Conditions of analysis* factor was not found to have a significant influence on the variables *Subjective experienced task difficulty* ($F = 0.35 < F_{2;45;\ 0,05} = 3.21$) and *Time of system analysis* ($F = 2.95 < F_{2;\ 45;\ 0,01} = 3.21$). Also, in Experiment 2, sketching does not prolong the time of system analysis, in spite of the greater amount of time needed to produce them.

Table 6 shows detailed results of Experiment 2.

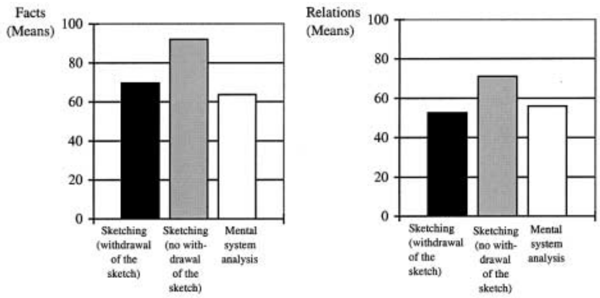

Fig. 2. *Experiment 2:* percentage of correctly reported facts and relations in different experimental conditions.

Table 6. Means (M) and Standard Deviations (SD) of dependent variables in Experiment 2

	Conditions of analysis A M (SD)	B M (SD)	C M (SD)
Percentage of correctly reported facts (in %)	69.7 (21.94)	91.9 (14.1)	63.7 (25.90)
Percentage of correctly reported relations (in %)	52.6 (14.37)	71.1 (19.60)	55.9 (14.99)
Time of system analysis (in minutes)	16.1 (5.98)	12.1 (5.30)	11.19 (6.41)
Experienced task difficulty 0 . . . very difficult 7 . . . not very difficult at all	2.1 (1.39)	2.1 (1.26)	1.8 (1.16)

A Instructions to sketch the facts and relations during system analysis (withdrawal of the sketch)
B Instructions to sketch the facts and relations during system analysis (no withdrawal of the sketch)
C Condition of exclusively mental system analysis, prevention of sketching

5. Discussion and Conclusion

The results of the studies presented warrant the assumption that the complexity of problems is decisive in determining problem analysis and representation. This corresponds with the current state of psychological research. The higher the mental resources are loaded during the analysis of the given problem, the higher the probability of inappropriate or incorrect representations, as well as incorrect operations on them (Dörner 1976, 1989; Anderson and Jeffries 1985; Klauer 1993). So, in these initial stages, it is essential to support the problem solver with external aids, such as sketches. The supportive aids shall be integrated parts of the analyzing and problem solving process, and these aids shall support the two main components of mental problem solving: maintaining the fullness of activated knowledge facts and currently received information (memory support) and processing the data, including its continual analysis when intermediate results are obtained (thinking support). Prior studies have already demonstrated the improvements in effective design solutions with the aid of problem sketching and modeling. It was proven that these sketches act not only as a memory support, but also as a thinking support. However, from these experiments, it was not possible to determine the benefit ratio of the process, i.e. sketching or modeling to the product of this process, i.e. sketch or model (Sachse et al. 1999).

The results of Experiment 1 suggest that the process of sketching itself supports the construction of a mental representation and, therefore, the problem analysis. In Experiment 1, the participants were asked about the facts and relations presented right after the analysis of the mechanical system. The participants who analyzed the systems without any support recognized fewer facts and relations, and reported a higher level of the experienced task difficulty. However, in Experiment 2, when the presentation of the questions was delayed, these effects could not be proven. The participants who analyzed the systems without any support did not differ from the participants who produced a sketch in addition to an exclusively mental system analysis. Only the participants who could fall back on their sketch while answering the questions differed significantly from the participants of the other groups. Therefore, the past assumptions of sketches as external stores can be verified (Schulz and Steinmüller 1978; Muthig and Schönpflug 1981; Schönpflug 1986; Ullman et al. 1990; Dörner 1994; Görner 1994; Sachse et al. 1999).

During the 20 minute period between the system analysis and answering questions concerning the system, the faculty of spatial imagination was measured (3D-cube-test; Gittler 1990). As a consequence, an interruption in content and time can be assumed. One reason for the missing support of sketching could be due to a reduced recollection of the mental representation of the mechanical system analyzed by interference of the test. Therefore, sketching can actually contribute to, as well as support, action regulation. The performed interruption contained a disturbance of the mental problem handling, but effective mental action depends upon uninterrupted and non-delayed working feedback circles. During the development of ideas, interruptions and delayed feedback disturb the problem solving process, and would prevent its progress in the worst case scenario (Sachse et al. 1999). Consequently, the effects of sketching on characteristics of a successful problem analysis, as recorded in Experiment 1, are restricted by an interruption of the process. If long-term storage of a mental representation is necessary, the sketch should be available as an external store, because of it is used only during the initial analysis process, the sketch cannot develop its supportive effect.

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