Original paper

Research in Engineering Design 14 (2003) 89–97
DOI 10.1007/s00163-002-0028-7

Support value of sketching in the design process

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Abstract This study presents an experimental investigation dealing with the support value of sketching activity in the early stages of the design process. The main focus is the process of sketching, including the sketching activity and the simultaneous use of the produced sketches. Sketching has a positive impact on the quality of the designed solution and on the individual experience of the design process. The quality of the solution concepts increases from entirely mental design problem solving without external support over partly supported to completely supported problem solving. On the basis of a representative case, the procedure of sketching and the activities performed while generating a design solution are analysed. A continuous change between internal mental and external materializing activities can be seen in the design process.

Keywords Design problem solving, Sketching process, Engineering design

1 Introduction

Because of the economic importance of designing, a demanding and complex problem-solving activity, it has been the subject of interdisciplinary research of psychologists and design engineers for several years. To meet the increased requirements of product development, the analysis of thinking and action processes and the search for specific support possibilities of the design process is central to this research. Therefore, the question arises of how and when support options should be used to achieve shorter development times and lower production costs while maintaining high quality demands. Of central importance for design results are the early stages of problem finding and analysis and conceptual design, in which 70–80% of production costs are determined (Ehrlenspiel 1995). Since in these stages the chances of correcting errors are the highest, the use of low-expenditure sketches and material models during design is crucial. Externalized representations fulfill various functions during the design process: they can serve as aids for analysis, solution generation, evaluation, and communication and as external storage (Sachse et al. 1999b; Römer et al. 2001). Self-made sketches, for example, support the limited human memory capacity and mental processing for a detailed problem analysis (Ullman et al. 1990; Pearson et al. 1996; Purcel and Gero 1998; Suwa et al.1998; Kavakli and Gero 2001). Since the design process is strongly influenced by feedback and dialogue, the communicative function of sketches is also of great importance in the daily design practice (Frankenberger 1997; Frankenberger and Badke-Schaub 1998). Sketching as external fixation of ideas calls for the early specification and testing of these ideas and thus reduces the vagueness and ambiguity of concepts. The development of useful ideas and concepts can be facilitated and hastened by the graphic form of a sketch or drawing (Rowe 1987; Fish and Scrivener 1990; Römer et al. 2000). Of major importance are the correctness and differentiation of mental representations because they determine the quality of the connected mental processes as well as of the regulated actions. Hunt (1987) points out that the early use of non-self-made models without the individual experience of modeling leads to an insufficient analysis of the problem, since prefabricated models do not meet the necessary requirements of support in engineering design. Until now research in design problem solving often focused on the use of external representations; there are only few findings about the support value of sketching and modeling. Field studies indicate that the effects of sketches and models differ from those of the activities of sketching and modeling (Sachse and Hacker 1995; Riemer 1996; Kavakli et al. 1999; Sachse et al. 1999a). The immediate feedback when viewing the developing sketch should be as beneficial as the reduction of complexity, which is a prerequisite to determining solutions. To date there are no secure results about the effects of this process on the timing and quality of the design solution.

Received: 5 June 2001 / Revised: 30 September 2002
Accepted: 17 November 2002 / Published online: 15 February 2003

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2 The process of sketching: support potential and effects

2.1 Research questions and hypotheses

This study focuses on the process of sketching and its support value in the early stages of the design process.

Basically, the study follows the successive elimination of the possibility to sketch with the simultaneous use of the self-made sketches. On the basis of the mentioned references, the following questions can be derived:

1. Does the sketching activity itself with simultaneous use of the self-made sketches—in the sense of partly supported design problem solving—offer support value in the early stages of the design process?
2. Does the support value increase in the following hypothetical order:

   (a) Without sketching and no use of sketches (entirely mental design problem solving without external support).

The following results are expected:

1. Subjects with external support by sketching and the use of the sketches up to a certain point in the design process achieve a significantly higher quality in their solution in the same amount of time compared to subjects who solve the design problem only mentally. They experience the problem to be significantly easier and are significantly more certain that their solution is correct than those who work out the design problem without any external support.
2. Subjects with unlimited support by sketching and the use of the sketches achieve a significant improvement of solution quality while requiring more solving time compared to both other groups of subjects. They experience the problem to be significantly easier and are significantly more certain that their solution is correct.

2.2 Method

2.2.1 Research design

The research is carried out by a laboratory experimental study, where people work alone on a design scenario. It is attempted to gradually limit sketching activity and the use of sketches. To test the first issue presented, the following group division was chosen:

1. Request to sketch—temporarily unlimited use of the self-made sketches (completely supported design problem solving) In this condition both the process of sketching and the continuous referral to the produced sketches have effects.
2. Request to sketch—revocation of both the self-made sketches and the possibility to sketch (partly supported design problem solving) At a certain degree of completion of the design solution both the sketches and the possibility for further sketching are withdrawn from the subject. Only the process of sketching itself and the timely limited availability of the sketches have effects.
3. Explicit demand not to sketch—no use of sketches (entirely mental design problem solving without external support) The design process is supported neither by sketching itself nor by the use of sketches; the design problem has to be solved entirely mentally.

The influence of these three experimental conditions on the dependent variables was tested using an analysis of variance. Furthermore, the procedure of sketching as well as parts and changes in the performed activities are analysed. Here the presentation is entirely descriptive using a representative case.

2.2.2 Subjects

The sample was composed of 45 students in the mechanical engineering graduate program and students majoring in other engineering programs in mechanical engineering at the Dresden University of Technology. The average age of the 3 female and 42 male subjects was 24 years (standard deviation SD=2.45). Random sampling resulted in three subsamples of 15 subjects each. Homogenous conditions could thus be assumed. Subjects were trained in design methods through their curriculum and/or internships on a comparable level. Analysis of variance for independent samples showed no significant differences in spatial ability (tested by using the short form of the three-dimensional cube test by Gittler 1990) or in motivation for dealing with the design problem (measured using five Likert scales with seven ranks each).

2.2.3 Design problem, analysis of requirements and research material

The subjects were asked to design a garden grill in written form up to the concept stage without time limitation. The grill had to meet certain fixed demands. For example, the distance between the grill and the brazier had to be continuously (not just gradually) variable. Neither the grill nor the brazier could be touched to vary or lock the grill height. Furthermore, both parts should be easily removable for cleaning purposes, and parts close to the brazier had to be heat resistant. The whole device had to be weather resistant and easily portable.

This design problem was devised by mechanical engineers of the of product development chair of the Munich University of Technology. Because of its features it could be classified as an adaptive design. The present structure of requirements was tested by a team of experts using a procedure for theoretical problem and task analysis (PAA) (Schroda 2000). The team was composed of design engineers and psychologists of the Technical Universities of Dresden and Munich (n=4).

How demanding the task is can thus be evaluated using the criteria *conflicting goals, complexity, transparence, degrees of freedom, dynamics* and *necessary knowledge* (Dörner 1976; Frost 1994; Hacker 1998). The evaluation of the named dimensions was done using several five-step ratings. The difficulty of the garden grill as a whole and of its subfunctions were evaluated separately to meet the various experimental conditions. Outcomes of the expert evaluation are shown in Table 1. The difficulty of the entire design problem was classified as medium. The difficulty of the grill and brazier as subelements was classified as rather low.

The subjects had to carry out the design scenario up to the conceptual stage. Two groups of subjects were asked

Table 1. Structure of requirements of the design problem (mean values, n=4)

Feature	Garden grill Mean values	Adjustability and lock	Grill and brazier	Rack
Conflicting goals	3.0	1.7	1.0	3.0
Complexity	2.3	3.7	2.3	1.0
Intransparency	2.8	2.7	1.3	4.0
Degrees of freedom	3.8	4.5	2.0	3.5
Dynamics	1.8	1.3	1.0	1.3
Needed knowledge	2.5	3.0	1.5	2.5
Total task difficulty	2.7	2.8	1.5	2.6

to sketch. Drawing paper and pencils were at their disposal. The first group could use their produced sketches with no constraints. They then verbally presented their solution, using those sketches. The sketches and drawing materials of the second group of subjects were withdrawn after they had completed 50% of the solution. To do this, the whole object "garden grill" (100%) was divided into ratable sections, and percentage values were assigned according to the difficulty and the required effort (mechanism of continuous adjustability, 50%; grill and brazier, 15% each; rack, 20%). After the sketches and drawing materials were withdrawn, the subjects were asked to solve the rest of the design problem without external support. The third group of subjects was asked to solve the problem entirely mentally without external support and thus had no sketches for later use. The second and third groups were asked to present their solutions verbally after they signaled its completion; afterwards they had to sketch it out all at once.

2.2.4 Dependent variables

The following dependent variables were recorded: quality of the solution, total solution time, experienced difficulty of the design problem and certainty regarding the correctness of the solution. Using a representative case, parts of the activities performed during the design process, their sequence and the proceeding strategy during supported and partly supported design problem solving were examined more closely. The technical quality of the design solution outcomes was estimated by a team of experts (n=3), composed of two designers and a psychologist. They used a technique following Langner (1991), who developed an evaluation scheme with the criteria *function, fabrication, assembly, design, simplicity, clarity* and *security*. With the aid of video protocols, each solution was evaluated according to the fulfillment of the posed requirements. According to the degree of fulfillment, a point value between 0 ("minimal fulfillment") and 4 ("nearly ideal fulfillment") was assigned. Taking the standard deviation into consideration, these single values were used to calculate a total value for each subject as a measure for the solution quality (Schütze 2000; Römer 2002). Total solution time was the time from the presentation of the design problem until the signaled completion of the solution. Both subjective criteria, the experienced difficulty of the design problem and the certainty regarding the correctness of the solution, were registered using bipolar rating scales ("very difficult" versus "not sure", and "not difficult at all" versus "entirely sure"). Video recordings and computer-aided protocol techniques were used for the registration of the activity parts. Hence the sketching process, with its individual activities and sequences, and the proceeding strategy in design problem solving were recorded.

2.3 Results

2.3.1 Solution quality

Significant differences in the quality of the produced solutions could be seen between the groups. The design results of the entirely supported subjects had a significantly higher solution quality than those of both other groups [(1)–(3): F=39,618; p<.001; (1)–(2): F=39,618; p<.05]. Furthermore, the solution quality of partly sketching subjects could be classified as significantly higher compared to that of subjects who solved the problem entirely mentally [(2)–(3): F=39,618; p<.05].

2.3.2 Total solution time

Entirely supported subjects needed significantly more time to develop the design solution than subjects who solved the problem entirely mentally or those who had only limited sketching time [(1)–(3)/(1)–(2): F=23,864; p<.001)]. The total solution time of partly supported designers did not differ from that of subjects who solved the design problem without external support [(2)–(3): F=23,864; p>.05].

2.3.3 Experienced difficulty of the design problem

Subjects with temporarily unlimited sketching abilities rated the design problem as significantly less difficult than did subjects who solved the problem entirely mentally [(1)–(3): F=3,252; p<.05]. The second group, where both the sketches and the possibility for further sketching were withdrawn at a certain point in the design process, didn't differ from either of the other groups [(2)–(1)/(2)–(3): F=3,252; p>.05].

2.3.4 Certainty of the correctness of the solution

No significant differences could be found between the three groups regarding certainty about the correctness of the solutions [F=,800; p>.05]. As a consequence, the stated hypotheses could be confirmed with the exception of the only partly secured effects of sketching on the two subjective criteria. These results are summarized in Table 2.

2.4 Representative case: sketching in early stages of the design process

We present a representative case of the experimental condition with entirely supported design problem solving

Table 2. Mean (M) and standard deviation (SD) for outcome and subjective criteria (N=45)

	Experimental groups		
	(1) Completely supported design problem solving M (SD)	(2) Partly supported design problem solving M (SD)	(3) Mental design problem solving only without external support M (SD)
Outcome criteria			
Quality of solution (%)	45.5 (2.8)***	38.7 (3.2)***/**	32.6 (5.4)***/**
Total solving time (min)	36.3 (19.0)***	10.3 (4.3)***	10.6 (6.3)***
Subjective criteria			
Subjective experienced difficulty of design problem[a]	5.6 (1.4)*	4.5 (1.6)	4.2 (1.7)*
Subjective certainty regarding correctness of solution[b]	5.2 (1.1)	4.5 (1.8)	4.9 (1.5)

*p<0.05; **p<0.01; ***p<0.001
[a]0, very difficult; 7, not difficult at all
[b]0, not sure; 7, entirely sure

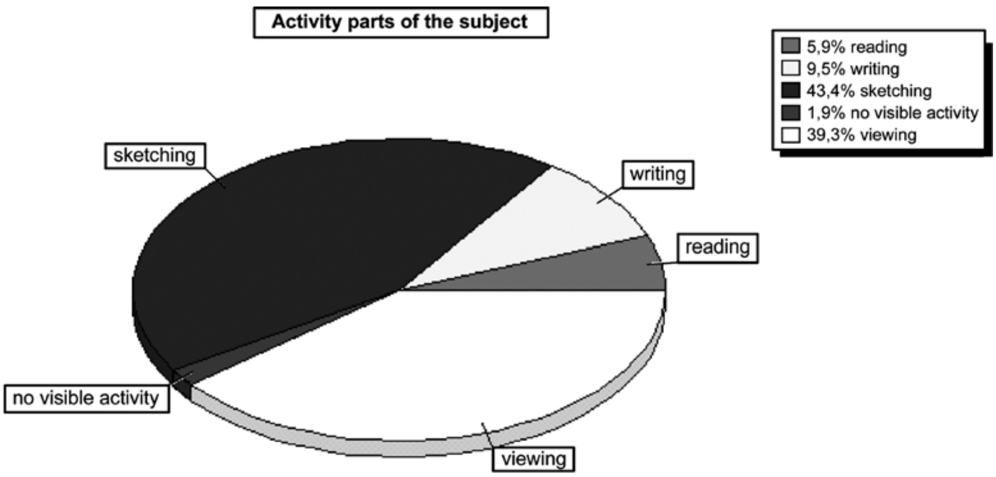

Fig. 1. Subject's activities

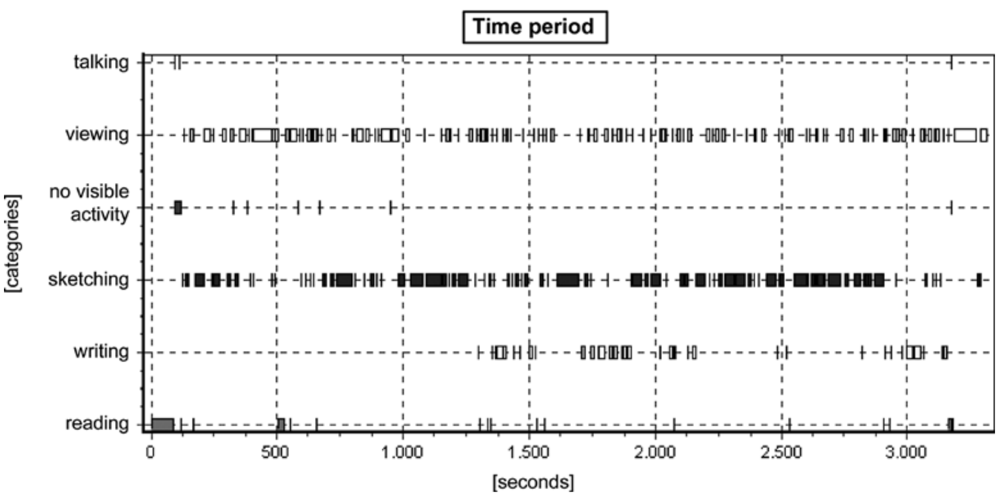

Fig. 2. Time progression of the subject's activities

in order to show the strategy of a person who generates a solution that is externally supported by sketching. To stress the process of sketching, the activity parts and their sequences as well as the sketching procedure are examined. The subject is a 25-year-old male mechanical engineering student in his 12th semester with practical experience. This student achieved an above-average result in the three-dimensional cube test (Gittler 1990) compared to the test sample. His motivation for the treatment of the task was only average (57.1%). He solved the task in 58 min and achieved an above-average solution quality value of 82.3%. He experienced the design problem as not

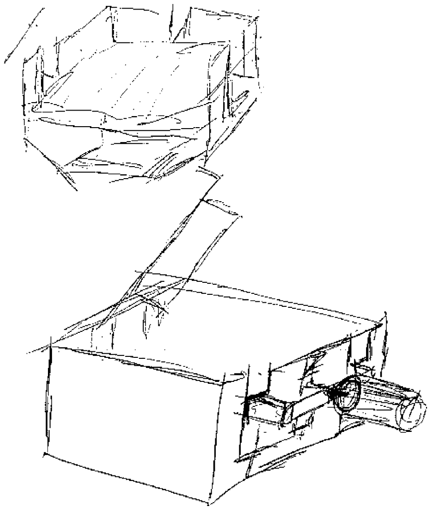

Fig. 3. Sketch 1 of the design

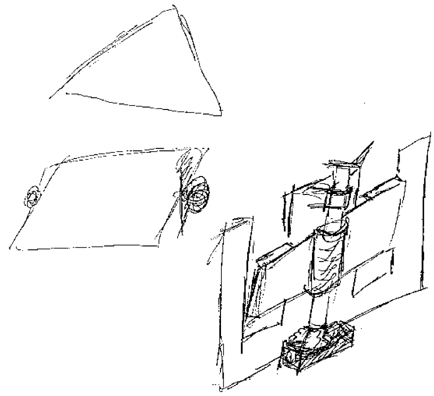

Fig. 4. Sketch 2 of the design

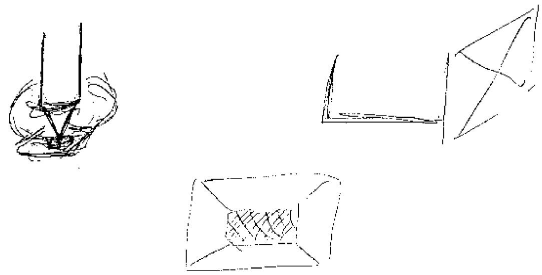

Fig. 5. Sketch 3 of the design

difficult at all (100%), but was only moderately certain of the correctness of his solution (48.6%).

2.4.1 Activities and time progression

From the receipt of the design problem until the completion of the solution, the subject performed several activities that can be categorized as follows: reading, writing, sketching/drawing, viewing (the sketch) and no visible activity (Schütze 2000; Römer 2002). These can be separated in purely internal (viewing, no visible activity) and external materializing activities (writing, sketching), which of course also involve mental processes. The division of the designer's activities is shown in Fig. 1. The equal emphasis of sketching and viewing is noteworthy.

The time progression shown in Fig. 2 gives a summary of the chronological sequence of the activities during the design process. At the beginning the subject reads the design problem for about one and a half minutes. Afterwards, there is a permanent change between sketching and viewing the sketch. One hundred twenty changes are recorded between internal and external activities until the solution concept is finished. The individual sequences last between 5 s and about 90 s. During the middle third of the design process, the subject annotates the sketching sheet with names of the individual drawn elements of the garden grill and the requirements to be met. With a certain regularity, the subject casts an eye on the given task description for 5 to 15 s. In the post-experimental oral interview he describes an initial need to clarify the specifications of the task and to return to this clarification throughout the design process.

2.4.2 Externally supported design problem-solving procedure

Next, the subject's method when generating the design solution with sketching support will be investigated more closely. In the oral interview the subject expresses that he transferred the solution from a similar problem with an analogous conclusion. He takes on form and functional characteristics from memory. As early as the first sketch (Fig. 3) he deals with developing a solution for the most demanding aspect of the garden grill: the continuous height adjustability. A first rough three-dimensional sketch showing the basic square form of the grill with a possible slide for the grill is used immediately for a second, far more detailed three-dimensional approach. This sketch retains the basic square form of the brazier with the integrated grill slide, but the number and order of the possibilities for the slide are developed further. This is a functional and static improvement. Although no measurements and/or elements of a technical drawing can be seen, one can follow the enrichment of the approach with important details leading from a "thinking sketch" to a drawing. The drawing in particular deals with the idea to attach the height-adjustable grill and its slide in the squarely covered model.

The first sketch shows height adjustability and attachment of the grill directly on the metal exterior of the garden grill. This is a simple but functional first solution. In the second sketch (Fig. 4) the subject first considers the basic form of the grill again. After considering a triangular alternative he returns to the original square version. Next he begins to design and develop a much more complex height adjustability with thread elements. The grill is to be moved indirectly over a vertical metal axle. Sketch 2 is a real detail cut, showing information about the slide of the height adjustability, but not about its drive.

The third sketch (Fig. 5) offers a first clue to that problem. It centers three-dimensionally on the constructive area of the metal axle bearing and presents a simplified friction bearing. The tapered metal point shown is fitted into a drill hole. The drawn element shows that the

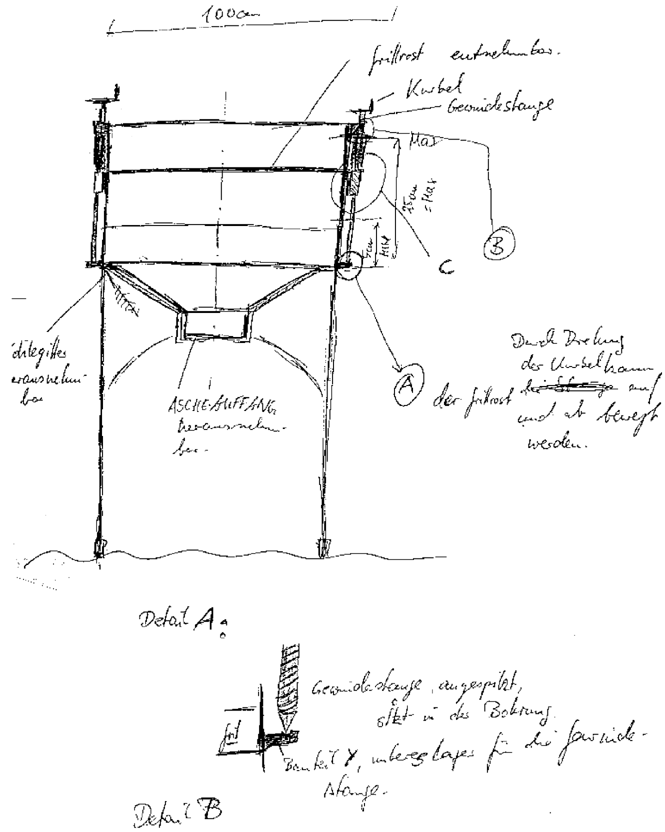

Fig. 6. Sketch 4 of the design

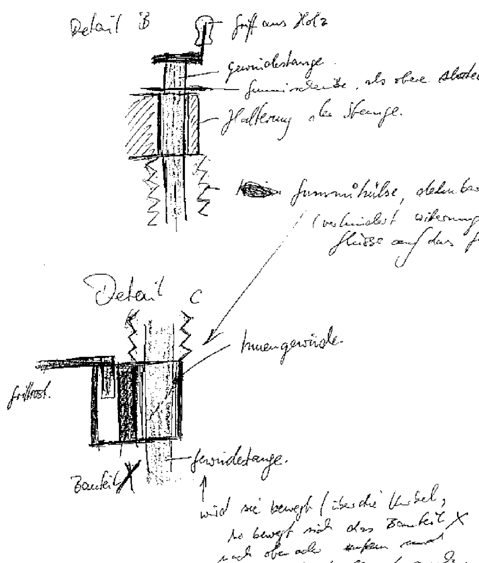

Fig. 6. (Contd)

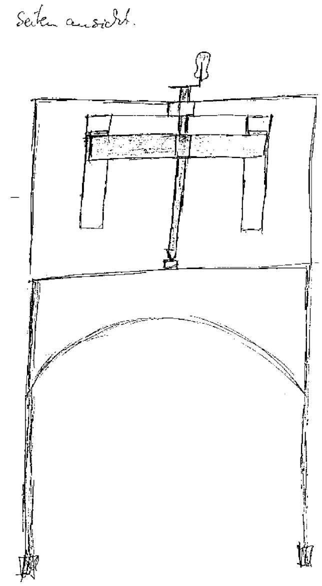

Fig. 7. Sketch 5 of the design

subject approached the problems of this height adjustability drive by first designing the more demanding design solution of indirect adjustability. He thus tries to solve the inevitably occurring problems of the bearing with a simple solution.

After the subject tackled the essential parts of the problem with sketches 1 to 3, the fourth sketch (Fig. 6) shows a two-dimensional design of a complete garden grill with all the elements of the earlier sketches. Even though it is drawn two-dimensionally and adequate measurements were in part applied, the sketch remains unclear and is incomplete with regard to central functions. For function-relevant design parts the subject added detailed sketches. These explain three-dimensionally what remains fragmentary in the two-dimensional sketch. He also annotates key points next to the detailed sketch, which are central for understanding the whole solution. Detail A again presents the axle bearing, which was central in the third sketch (Fig. 5). The metal axle, however, has been modified and is now executed as a threaded rod. This again points in the direction of further development of the solution, especially the height adjustability, since milled threads demand a different mechanism. It becomes clear that the decision of the subject to change the vertical mechanism leads to the more complex solution of the mechanically moving parts.

In details B and C, the design of height adjustability of the grill (only hinted at so far) is presented two-dimensionally. The total functionality can be determined and is connectable. By turning a crank, which is connected firmly with the threaded axle, the grill experiences a positive axial–vertical thrust and moves upwards. The primary moving thrust element is a milled metal body, which changes turns of the crank with respect to the threaded axle into a vertical movement. The grill can thus be adjusted vertically to the desired height. Furthermore, it is simply hung onto the metal body and is removable at all times. The subject succeeded in reducing the difficult problem of the adjustable height to a simple mechanical system. Through the movement of the grill over the threads, it is no longer necessary to lock the height adjustability, since friction at the thread and axle end will always be greater than that caused by the grill moving in a negative vertical direction. The approach in sketch 1 was considerably developed and qualitatively improved with this relatively simple solution for the main problems of the

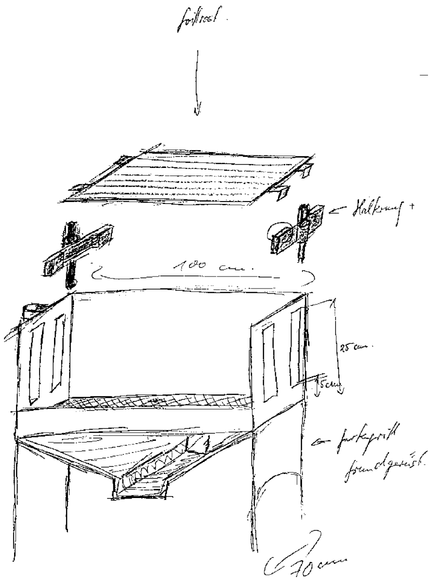

Fig. 8. Sketch 6 of the design

garden grill. With sketch 5 (Fig. 7) the subject presents another two-dimensional side view of the garden grill with the essential components.

Besides the developed and described elements, he goes back to the model presentation of the second sketch (Fig. 4) as a final solution for the grill slide in the square metal cover. With sketch 2 he developed an early approach, which had only to be modified in its less important mechanical details. In the sixth sketch (Fig. 8), the garden grill is finally presented as a three-dimensional explosion picture in which the subject points out removable parts like the grill and grill slide. Again, this sketch contains elements of a technical drawing, and additional text elements are added to give a complete grasp of the final solution.

In the oral interview the subject stated that he could not have solved the problem without the possibility to sketch. Sketching serves several functions for him: it acts supportively during analysis, serves as support for the imagination and assists in developing and testing the solution.

3
Discussion

The presented experimental study was developed to obtain results about the influence of the sketching activity on the outcome and subjective criteria in the early stages of the design process. A sample of mechanical engineering students was instructed to design a garden grill with several requirements. The possibility to sketch with the simultaneous use of the sketches was gradually limited in the three subsamples.

3.1
Influence of sketching on solution quality and solution time

As expected, significant differences between the experimental groups were found regarding the solution quality. Subjects who solved the design problem partly supported by sketching achieved a significantly higher solution quality compared to those whose problem solving was entirely mental. The solution quality of entirely supported designers was rated as significantly higher than that of the other two groups. However, they needed significantly more time for solution generation. This can be attributed to more comprehensive solutions as a consequence of unlimited sketching time. To a large extent, they produced several alternative solutions, both for the garden grill as a whole and for individual elements. These were often not only modified but also optimized in quality. The experimental groups who were partly supported and those who used entirely mental designs did not differ significantly with regard to total solution time. This result points out that in the limited access to sketching condition, the extra time needed for sketching was compensated by the supportive effect of sketching with the simultaneous use of the sketches. This result concurs with the hypothesis and supports the findings of Sachse (1999, 2002), Riemer (1996) and Leinert (1997). At the same, the time solution quality was higher compared to the group whose design was performed entirely mentally. This points to a support value of the sketching activity. In comparing the subjective aspects of the two latter subsamples, no significant differences could be determined. This is contrary to the stated hypotheses and gives reason to suppose that the problem was underestimated and not treated to its full extent by non-sketching subjects. This is connected to the lower solution quality of this group, whose solutions often do not meet all the posed requirements. As expected, subjects who solved the problem completely supported experienced the design problem to be significantly less difficult than both other samples. No significant differences could be found regarding the subjective certainty of the correctness of the solution.

3.2
Functions of sketching

Statements of the completely and partly supported designers in the post-experimental oral interview regarding the functions of sketching agreed with those of a survey among designers who identified the functions of external support in the constructive design process (Römer et al. 2001; Römer 2002; Riemer 1996; Sachse and Hacker 1995, 1997; Hacker 1998; Sachse 1999): Sketching served as an aid for analysis, short-term memory, communication and documentation. It proved to be helpful for the development and testing of solutions as well as for the identification of errors. Because of the features and functions of the sketching activity, which were experienced to be supportive, it is even more surprising that two-thirds of the 45 subjects were of the opinion that the design problem could have been solved with no further problems without the possibility to sketch.

3.3
Sketching procedure

The presented representative case illustrates the following general observation: the sketching procedure does not point to an immediate, systematic treatment of the posed requirements. Sketching was used for describing a thought through fixation on paper in a figurative and vivid way. This visualization seemed to happen in the sense of an active elaboration. According to the subject's own statements, it had a memory-relieving function. Considering the striking interplay between internal and external materializing activities, it becomes obvious that sketching activity alone, without its materialized product, is not sufficient to support the generation of a solution. If long-term storage of a mental representation is necessary, the sketch should be at the designer's disposal at all times, serving as external memory (Römer 1998). Such an intensively used reciprocity of materialized and mental activities leads to the conclusion that effective design problem solving depends on an undelayed feedback loop of seeing, imagining and drawing. The activities of sketching and viewing the self-made sketch were like an "objective" act in the design process: Subjects gained distance and entered, in a way, a metalevel (Hacker 1999). In this way, the "resistance of reality" showed itself in the form of the sketched visible state of affairs. The content of the sketches gave impulses for further proceedings. Newly discovered, relevant knowledge was integrated step by step. Sometimes a complete rejection of the sketched idea was necessary, since it proved to be not functional after close analysis. At other times the basics of the idea could be retained, while details needed modification. Sketching enabled the designer to "experiment with reality", to learn from the experiment and to iterate the solution space. These early sketches were of low artistic quality. They did not have to represent reality with fidelity; they were sufficient to support critical thinking and alternative generation. Because of the vague and undetailed representation, the designer had various open possibilities to change and improve his ideas. So sketching corresponds to a snapshot of the cognitive activities of the designer, which become "tangible" in the form of the sketch. The sketch as an outcome of the cognitive process can be used interactively to support design thinking. This correlation between thinking and sketching leads to a solution that is solidified and precise as well as differentiated and/or corrected. Because partly supported subjects had their produced sketches available up to a point, the support value of the sketch as an object and sketching as an activity could not be separated clearly in this setting. Actually, this separation is of low practical relevance. The findings of this study show that the process of sketching, which includes the activity of sketching with simultaneous use of the produced sketches, has a positive effect on the solution quality of design outcomes in the early stages of the design process. This is also true if sketching is only temporarily possible. It must be said though, that the quality of design often does not become obvious until the stages of assembly and use, as in the aspects of acceptance on the market and satisfaction of customers.

3.4 Outlook

Further studies are necessary to investigate whether the same result could be achieved if the design problem was different, for example, more complex. Another interesting point is the influence of sketching skill on outcome and subjective criteria. It could be assumed that an enhanced sketching skill improves the quality of the solution and shortens the process of finding a solution as it binds fewer memories.

Results regarding the activity of sketching help to develop suitable digital sketching tools, especially for the early stages of the design process. Because of the ergonomic concepts of hardware and software, these tools can create potentially large time and cost savings for computer-aided design in mechanical engineering. Experimental studies about the support value of digital sketching tools, which allow intuitive work similar to traditional sketching, are not yet available. Further work dealing with the possibilities for the integration of sketching in computer-aided design to make it a tool also for concept development in the early phases of the design process is in progress (M. Schütze, 2002, personal communication).

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