Bei diesem Beitrag handelt es sich um einen wissenschaftlich begutachteten und freigegebenen („reviewten") Fachaufsatz.

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Action Theory – A Generic Approach to Design Activity

Konstruieren als Arbeitstätigkeit

Abstract *Empirical research in engineering design indicates procedural characteristics which improve solution quality: Opportunistic strategy; combination of thinking by head with thinking by hand (sketching); question-based reflection of own results. They correspond with predictions of the generic theory of mental regulation of working activities („Action Theory").*

Inhalt *Empirische Untersuchungen des Konstruierens zeigen Vorgehensmerkmale, welche die Lösungsgüte verbessern: Opportunistisches Vorgehen; Kombination von Denken im Kopf und mit der Hand (Skizzieren); fragengestütztes Reflektieren eigener Ergebnisse. Sie entsprechen Vorhersagen der Theorie der psychischen Regulation von Arbeitstätigkeiten („Handlungsregulationstheorie").*

1 Introduction

Current approaches of design thinking consider only some aspects of design. Action Theory offers a number of more appropriate additional aspects. Following Action Theory, three main issues of the regulation of mental working activities are discussed for engineering design based on field and experimental studies:

(1) the approach of an "one best entire strategy" of design versus a number of specific individual procedural characteristics that correspond to increased solution quality
(2) the interaction of internal (mental) and external (psychomotor) action components, specifically for the role of sketching as a "thinking tool"
(3) the reflective type of executive action control, analyzed with respect to the contribution of communicative versus solely cognitive question answering techniques.

In spite of the increasing body of results on mental characteristics of mechanical engineering design, there is as yet no one accepted theoretical framework that can explain and organize these results. In the literature on engineering design the design process is often described solely in terms of design thinking or design problem solving. From a psychological point of view, however, this approach considers only some aspects of the design process. Along with thinking processes (e.g., reasoning), the design process is a knowledge-rich procedure that depends on long-term memory recall, and a process with essential external psychomotor components (e.g., sketching, impromptu-modeling, or speaking). Moreover, design activities are goal-oriented working tasks.

Therefore, we propose a framework for engineering design not in terms of separate mental functions but in terms of a complex working activity and consequently apply the more appropriate approach of Action Theory in the tradition of Lewin [1].

Following this framework, three main issues of regulation of mental work activities will be discussed for engineering design.

2 The one best strategy vs. a number specific individual procedural characteristics of design?

There have been a large number of field and laboratory studies on engineering design strategies in recent years. A review has recently been undertaken by von der Weth [2]. His most important conclusions are:

(i) in a lot of cases a mismatch exists between observed design procedures of experienced designers and the strategy recommended in Design Theory (Pahl and Beitz [3]) and in standards, for example the German VDI standard 2221;
(ii) moreover, different designers apply different strategies depending on their different experiences. The review summarizes that "there is no one best design strategy of everybody" (von der Weth [2]: pp. 83, 95, 103).

Thus, on the one hand there does not seem to be one best strategy of design, whilst on the other hand a number of individual procedural characteristics are reported that seem to correspond to successful results, at least in the majority of cases (for a review see von der Weth [2]). Such characteristics are:

- a thorough analysis of the requirements of the task,
- the comprehensive exhaustion of relevant information,
- a dual, graphic and conceptual description of essential parts of the problem solving procedure with a frequent switch between them,
- the search for alternative solution principles, and
- a reflexive evaluation of results.

From an Action Theory point of view, just these are the characteristics of successful action regulation.

If the term "strategy" is defined as a generic heuristic decision rule selecting sequences of goal-oriented actions, it would seem to be

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Procedural Characteristics	Solution Quality highest (M ± SE)	Solution Quality lowest (M ± SE)	Significance of difference
Total time consumption (min)	43.3 ± 5.1	21.3 ± 3.4	0.01
Time share of mental processing (without external activity) (%)	2.6 ± 0.2	0.6 ± 0.3	0.05
Share of participants developing alternatives (%)	50	0	0.05
Mean frequency of switches total system/ Components	2.9	1.2	0.05

Table 1

Comparison of procedural characteristics of design activity (two subgroups of participants with best (n_1 = 10) vs. worst (n_2 = 10) solutions: Mean (M), standard error (SE)

Note: Hacker and Wetzstein 2004

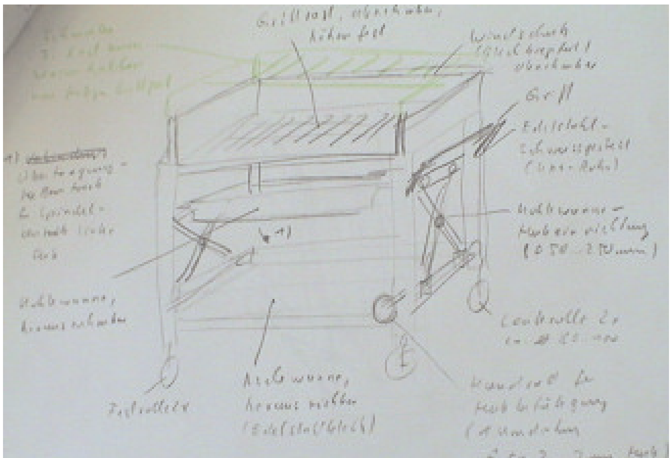
Dependent Variables	Without Sketching	With Sketching	Significance	Effect Size
Procedural Characteristics				
Total number of steps among them	40.2	25.6	0.01	0.81
Preparing steps	7.1	4.5	0.01	0.77
Repeated steps	3.4	1.7	0.01	0.75
Positioning steps	20.4	14.1	0.05	0.71
Correcting steps	3.0	1.4	0.01	0.78
Testing steps	6.2	3.8	0.01	0.80
Performance Characteristics				
Quality (number of correct parts)	4.0	3.7	ns	
Solution Time (min)	12.5	13.5	ns	

Note: 3-D program "Caligari true space"; ns ... not significant

Table 2

Procedural characteristics (M) in CAD-work without vs. with manual sketching [7]

Note: 3-D program "Caligari true space"; ns ... not significant



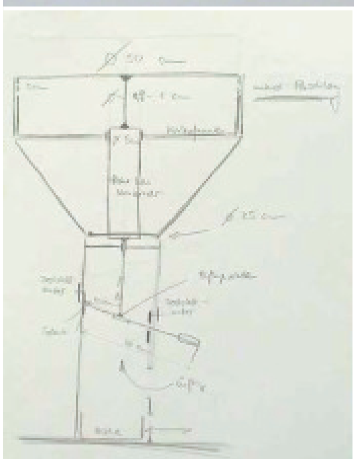


Figure 1

Examples of a design sketches

too demanding to identify actual strategies of design as implemented in real working situation. Therefore we restricted our investigations to the question whether in a sample of lay participants without any training in design methodology procedural characteristics that correspond to the quality of their results could be found. We investigated this issue in three experimental studies reported in Wetzstein and Hacker [4]. The participants (n = 204 students of the Technical University Dresden) were asked to design a specific type of garden grill. They received a list of requirements and were asked to make a detailed hand drawn 3-D sketch, which did not need to be true to scale. Restricting the analysis to a comparison of subgroups of participants with the best (n_1 = 10) versus worst (n_2 = 10) solution quality, it could be shown that (table 1) a higher solution quality corresponded to a higher total working time, a higher share of time for mental processing (thinking and reflection), a higher share of participants developing more than one solution (i.e., presenting alternatives), and more frequent switches between working on sketches of the total system and sketches of system components.

These differences could be verified with the total group of participants. Thus, the assumption is reinforced that – regardless of the missing "one best strategy" – a number of specific procedural characteristics correspond to better design results. Further research is necessary.

3 Interaction of internal (mental) and external (psychomotor) action components – the example of sketching

Action Theory describes jobs in terms of an interaction of their internal, or mental, and external, or psychomotor components. The Theory of exteriorisation/ interiorisation of actions (Galperin [5]) offers a model of this interaction. Design activity includes mental as well as psychomotor components that contribute both to "thinking in and by action".

Following this approach we considered four issues concerning the functions of sketching in mechanical engineering design:

Is sketching still relevant in CAD-work?

A survey of 106 mechanical engineering designers (Römer, Weißhahn, Hacker, Pache and Lindemann [6]) revealed that manual sketches are still widely used before and even during CAD-work. About 70% of the designers reported sketching in preparation of CAD-work and 60% during this work. More than 90% reported "developing solutions" along with "supporting communication" as their main intentions for using manual sketching in CAD-work. 3-D-CAD therefore does not replace free-

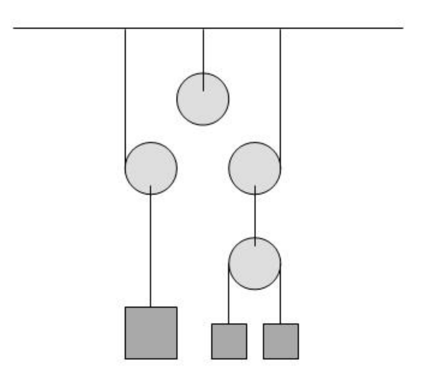


Figure 2

Example of a mechanical system

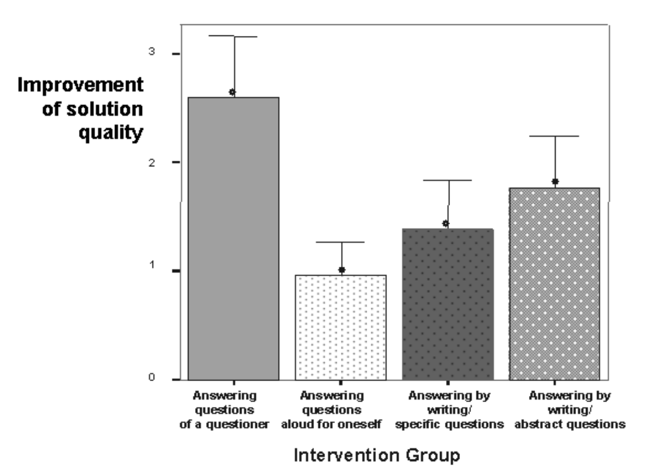


Figure 3

Improvements of finished designs after interventions (difference pre-/post): means of groups and standard errors; all groups improved significantly (each p < .01); the improvements do not differ significantly (F = 1.56, p > .05)

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hand sketching but instead initiates an interactive, hybrid procedure.

Which characteristics of the mechanical engineering design procedure are modified by sketching?

A sophisticated analysis requires an experimental design and a statistically sufficient number of participants, with comparable training and experience working at an identical task. A series of experimental studies of this type were carried out in our Dresden group (for a review see Sachse [7]).

Table 2 illustrates the results of a study with 76 engineering design students of three European universities who were asked to design a drive assembly with a 3-D-CAD program.

In one group the participants were requested to sketch manually before designing on the computer, whilst the other had no possibility to sketch beforehand. The sketches were monochrom line drawings, without shadowing or color, with uniform line thickness.

An analysis of variance revealed a significant difference between the total number of working steps and the different sub-types of these steps. Especially the number of repetitions, corrections and test operations are reduced by previous sketching without extending the total working time.

How to explain these modifications of the surface structure of design activity by sketching?

Sketching (1) may serve as an external memory of externalized, pre-existing ideas, (2) may offer a physical setting – the "humus soil" – in which thoughts are constructed mentally, and/or (3) may generate thoughts on its own. This last possibility – that ideas emerge through sketching – corresponds with the "visual thinking" approach (Goldschmidt [8]). In the cited survey and in other interview studies, experienced designers argued that manual sketches are not only mnemonic aids but, moreover, improve the developed solution principles, i.e., they are thinking tools too.

Figure 1 shows examples of manual sketches of a specific garden grill to be designed.

Although these statements seem convincing it is difficult to verify the latter claim from the point of view of experimental methodology.

Therefore, we again used experimental studies in order to investigate the role of sketching as a thinking tool. In the study we refer to here (n = 60, students of the Technical University Dresden) we analyzed an early stage of design-task analysis. The participants were asked to answer questions concerning the components and the relations within mechanical systems. Figure 2 illustrates the type of the mechanical system.

The written descriptions of these systems were presented only at the beginning of the session. In one group the participants were asked to sketch the system before the questions were asked, whilst in the other group there was no possibility to sketch. The sketches of the first group were removed before answering the questions. The results showed that sketching did not improve answers on system components, which could be remembered from the description. However, it significantly increased the correct responses on relations within the system, which were not presented directly in the descriptions but had to be deduced by reasoning (table 3).

Thus, at least for this type of task, sketching actually improves thinking. These results correspond with the approach of a cyclic interaction of mental, possibly conceptual, and visual, or rather sensumotor, components (Goldschmidt [8]).

Consequently, in terms of Action Theory, the outlined modifications of design by sketching are determined by improvements in the mental deep structure, i.e. the action regulating thinking processes.

4 Reflexive regulation of design activity

The notion of reflection in and on action is well known (Valkenburg and Dorst [9]). In Action Theory self-evaluation of the procedure and/or results is a decisive component of a reflexive type of executive action control. However, there are only a few well designed empirical investigations into the impact of reflection on the designing of objects.

In a series of experimental studies, we were interested in the specific question whether reflection on own solutions, subjectively perceived as finished, i.e. reflection at the very end of a design process, may further improve the solution quality. The independent variable was the type of reflection:

Dependent Variables	Analysis without Sketching		Analysis with Sketching		Differences and Effect Sizes concerning Sketching					
	low	high	low	high	low Complexity			high Complexity		
	Complexity		Complexity		Diff.	Sign.	Effect	Diff.	Sign.	Effect
Correct System Components (%)	84.4 ± 2.9	72.9 ± 3.7	93.6 ± 2.0	75.3 ± 3.9	9.5	ns		2.4	ns	
Correct Relations (%)	90.8 ± 2.1	62.0 ± 3.9	94.1 ± 2.2	82.5 ± 3.3	3.3	ns		20.5	0.01	0.93
Solving Time	6.5 ± 0.4	7.7 ± 0.5	6.0 ± 0.4	7.7 ± 0.4	0.5	ns		0.0	ns	

Note: ns ... not significant

Table 3

Results of task analysis in mechanical systems with and without sketching (means, standard errors, effect-sizes) [7]

All participants had to answer a list of the so-called "W-questions" (why, whereby, what reason, what of ...) that cause people not only to describe, but, moreover, to offer reasons for, to explain and to justify their solutions.

150 students of the Technical University Dresden without any training in design methodology designed a specific garden grill. In a first group the experimenter asked the "W-questions" with regard to the sketches and the participants answered them. The participants of the second group were given the questions in written form and asked to answer aloud to themselves. The participants of the third and fourth groups were again given the questions in written form but had to answer in writing. The difference here is the degree of abstraction of the questions.

All four groups achieved significant improvements in the solution quality after the interventions. However, these improvements did not differ significantly between the groups (figure 3). Further studies could support these results.

Consequently, reflection on design results, that is a reflection without interruptions of the design process itself, can improve the designing of objects significantly and with high effect-sizes. These improvements are due to a specific dialogue-type of thinking. Thus, the enhancement of solution quality is a result of the cognitively enriched regulation of action. The question and answering reflective procedure creates an interaction between the visual and the conceptual mode of representation and thinking.

5 Conclusion

In summary, Action Theory actually seems to be a theoretical framework that covers essential characteristics of engineering design and offers helpful guidelines for further research in design as for design in industry itself.

Practically, the management should offer possibilities of manual sketching, before and during CAD-work, and support sketching.

Further, question-based reflection at least at the end of the "early phases of design" (VDI 2221) by means of non-product specific questions should become a systematic component of design education and of the professional self-management of designers. In a recent application of these questions by experienced designers, 73% of them modified their solution and 42% thereof could improve them. Initially, the adoption might be supported by an application in the presentation of results and group discussions.

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