Sachse, P. & Furtner, M. (2009). Embodied knowledge in design. In K. Leidlmair (Ed.), *After Cognitivism. A Reassessment of Cognitive Science and Philosophy*, pp.163-179. Dordrecht: Springer.

Embodied Knowledge in Design

Pierre Sachse & Marco Furtner, University of Innsbruck (Austria)

1 Preliminary remark

In summary, our contribution contains two main focuses, which are interwoven with each other:

- the generation, activation, and use of knowledge during the process of finding a solution in the procedure of creative design, and
- the knowledge safeguarding in terms of often unnoticed artefacts of work (concretion) in the design process (sketches, material models).

For instance, design activities include the design of machines, of software, of technological processes, of organisational concepts, or civil engineering; the development of new medicine, teaching, or therapy method. We focus on designing constructively, i.e. designing "hardware". Engineering is not a thinking about given circumstances but rather a thinking ahead, i.e. a designing of not yet given circumstances by thinking, e.g. thinking of a not yet existing structure in the future. Thinking ahead should at least have partly creative qualities as the new structure should exhibit new and useful qualities. Concerning its outcome, designing should include uncertainty. There is a contradiction between the inducement to come to reliable solutions with one's own operations of thinking and the impairing risk of having to take detours by doing so or even failing. This is intensified by the fact that as far as designing activities are concerned, it can never be ascertained beyond doubt whether the developed result is actually the optimal one (Bucciarelli, 1994). All in all, the thinking in the process of constructing and designing faces demands which are not satisfiable in an optimal and rational way (cf. the concept of bounded rationality, March, 1978). Designers simply cannot go back to already found solutions when it comes to a variety of demands.

They face design demands which are vague and formulated both incompletely and blurred since, for instance, possible restrictions are still unknown or unrecognised in the early stages of the designing process, but might rather be a result of the development process itself (see figure 1).

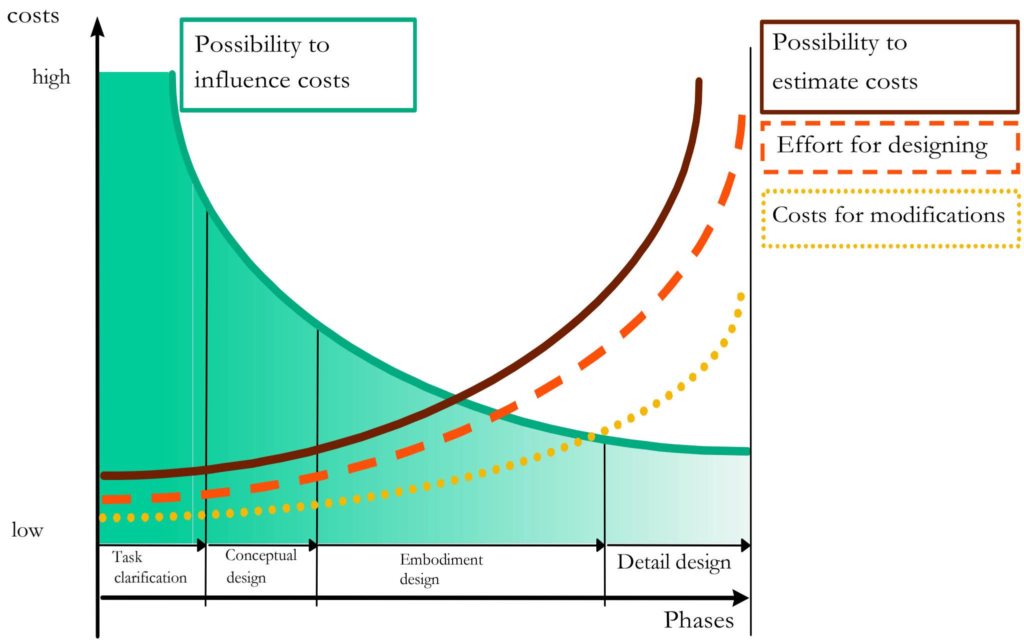

Figure 1: Phases of the design process and costs (Ehrlenspiel, 1995; 2007)

Thus, designing is not just the solution to given problems, but also problem finding itself. An exclusively experience-controlled processing as a matter of routine is not possible.

It is crucial that the most elusive early steps of task resolving as well as the conceptual design and pondering of fundamental solution possibilities have decisive influence on the innovation of the solution and manufacturing costs. Ehrlenspiel (1995; 2007) has clarified this in regard to cost influencing: It is incomparably higher at the early steps of the "problem- / task clarification" and the "search of solution alternatives", but at the same time also least certain to be assessed. At present, a sure judgement of costs will only be possible if it is too late for cost-saving consequences at an exact consideration.

Gaining access to relevant knowledge and earlier problem definitions is of central importance regarding the mastering of "design problems". In general, the *knowledge rich* design problems of everyday life designing are different from the well defined, *knowledge clean* or *knowledge poor* problems, which are examined in "classical" cognitive psychology. At common so-called “brain-teasers”, the solution can be obtained with knowledge that develops from the understanding of the instruction and the progressive process. On the other hand, the generation, activation, and organisation of a comprehensive set of different knowledge contents is in the fore as far as design development is concerned. The access to externally stored information is of importance. The knowledge retrieval alone does not help finding the complete solution (Sachse, 2002).

It proves to be helpful starting out from the following classification of action leading knowledge forms:

- *System or factual knowledge* (how-it-works-knowledge), which produces and is not completely stored (e.g. the knowledge about a cylindrical roller bearing),
- *Procedure, method, or rule knowledge* (how-to-do-it-knowledge), which is stored in the long-term memory (e.g. the area specific change knowledge of the calculation of a screw connection),
- *Heuristic knowledge* as area general knowledge of change.

Furthermore, a meaningful form of knowledge for design activities is the neglected *non-linguistic and sensory knowledge, which is obtained by touch and muscle feeling*. For this purpose, it is indispensible to deal actively with design objects, materials, etc. Also, essential elements of method knowledge during designing are ascribed to the heuristic knowledge since it contains methods for the analysis of design problems as well as for both search and judgement of solutions, and for the planning of the design process. The thinking psychologist Dörner (1994, 160) comes to the following realistic conclusion: “Which heuristic knowledge a … designer possesses, how that designer uses his knowledge in the process of designing, how he generates and uses ephemeral memory structures, or how he obtained those structures during his work experience is … uncertain.”

The features of designing miscellaneous objects successfully by different persons as well as the features concerning the procedure of successful or professionally experienced designers are summarised in the following (cf. Hacker, Sachse & von der Weth, 1996; Hacker, Wetzstein & Römer, 2002; Hacker, 2005; Hacker & Sachse, 2006; Müller, 2007). This feature pool contains:

- Analysing comprehensively the requirements and the information about the object to be developed (at the beginning and during further procedure; Dylla, 1991; Lindemann, 2005). Successful persons particularly take into account the information relevant for functioning, which they integrate and fix more frequently than other designers (Görner, 1994).

- Making extensively use of knowledge and information, whereby new insights and information, which both arise during the course of designing, will be proceeded in a target-oriented and flexible manner (Fricke, 1993).
- The parts of the system which are to be developed are processed one after another in detail on the basis of a rough temporary idea of the global solution. Working on the complete system alternates with detailed working on parts in terms of section-oriented procedures (Fricke, 1993; Günther, 1998).
- Different principles of solution are developed for complete and partial solutions. There is a generating and not only correcting solution production. From these alternatives, that solution will be selected which appears to be convenient (divergent and convergent thinking, Ehrlenspiel, 2007).
- During developing, sketches will be produced, i.e. visually apparent represented, as well as operated conceptually at different levels of abstraction (multimodal solution development, Dylla, 1991; Eisentraut & Günther, 1997; Roozenburg & Dorst, 1998).
- Reflexive assessments of the intermediate results and one's own procedure are carried out in repeated recourses upon the requirements defined in the functional specifications, and further steps are determined (Eisentraut & Günther, 1997). This is the case as far as the general solution principle and the concrete individual solutions are concerned.

2 Knowledge application and artefacts of work

Designers change between the use of existing knowledge (e.g. solutions already known by adaption) and the production of new knowledge (e.g. by the development of new solutions). In this way, a constantly recurring change of knowledge structures takes place due to new design requirements and knowledge within the design process. Both internal (e.g. mental "models", problem knowledge) and external knowledge sources (e.g. manuals, databases, design drawings, rough sketches, material models) are used during processing and solving of "design problems". The reason therefore is: *Knowledge is not only represented cognitively, but also externalised in technical artefacts among others*.

New product ideas of creative designers are developed, put in concrete terms, and fixed by use of hand sketches despite most modern digital means of work (e.g. CAD and VR systems; see figure 2). Moreover, complicated design problems as well as innovative ideas of solution are illustrated three-dimensionally and made conceivable by means of low-cost material models made of paper, cardboard, clay, wire, polystyrene, etc. (see figure 3).

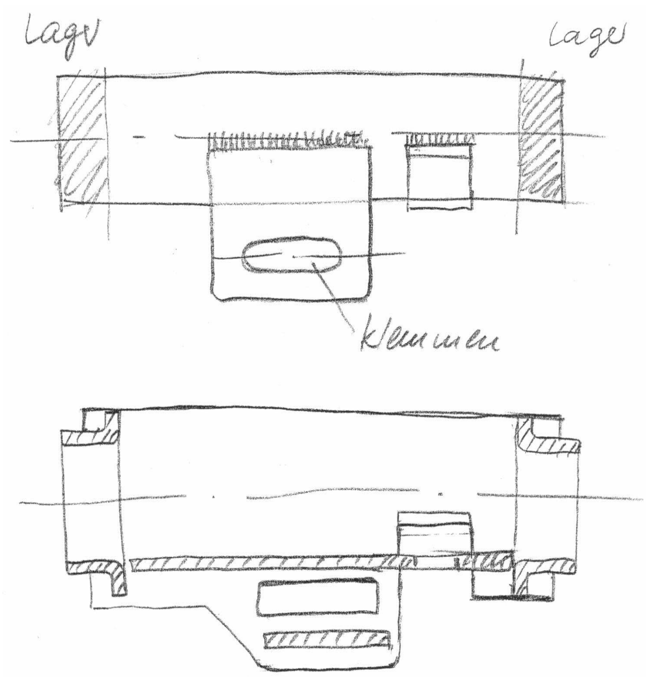

Figure 2: Sketches (Collection Styner & Bienz AG, Niederwangen)

Figure 3: Simple and low-cost material model before the process of sketching and drawings (Collection Styner & Bienz AG, Niederwangen)

Excursion: Sketches and material models

The sketch consists of few lines to clarify an order, a principle, or a form. It serves, among others, the aim of approximately formulating thoughts and ideas for solutions, illustrating, trying out, putting in specific terms, and fixing. In addition, functional, spatial, and design structures will be sketchily sampled, solution variants graphically surrounded, and the approach visualised. Compaction, coding, and abstraction take place during the process of sketching. An abstraction always means a diminution in which sketching reduction does not necessarily have to make poorer if it already contains the essential information. Complex contents and concrete forms will be linked together in their interaction.

The designers often design starting out from an uncertain general impression into an increasingly more certain detail.

They “abstract the solution variety to a simple thought model. This totality already contains all broader details in essence, which … unfolds in the process of conceptualising. Designing therefore is … an ongoing clarifying of partial functions which are to be fulfilled and a classifying …, an holistic-analytical process, whereby the designer operates inventively at two different levels: Firstly, he uses … ‘preconsciously’ … certain abstract structures of designing; secondly, he ‘consciously’ sketches specific … elemental combinations” (Bach, 1973, 4).

During sketching, a figure will be formed by trying, which is to detect and correct possible problems and disadvantages until an optimum seems to be reached. Uhlmann (1995, 79) characterises these facts as a "soliloquy with reply" – therefore, as a gradual process of the approach of aim and solution ideas towards the solution.

According to Ferguson (1993; cf. McGown, Green & Rodgers, 1998; Sachse, 2002; Buxton, 2007), three kinds of sketches are distinguished, which also provide an indication to their different functions within the design process:

a) *thinking sketches*, to conduct and focus the design thinking during sketching;

b) *prescriptive sketches*, which are the basis for the complete technical drawings in the future;

c) *talking sketches*, which are created during common discussion and revising of design problems by the designer him- or herself or by conversation with clients.

In the design process, the sketches are used in all course phases, on which diverse demands are made and by which different functions are fulfilled. The main focus of the manufacturing and the use of sketches is located in the early phases of the design process (cf. McGown, Green, & Rodgers, 1998; Hacker, Sachse, Wetzstein, & Winkelmann, 2004; Hacker & Sachse, 2006).

The sketches are most frequently used for the development of problem-solving approaches, less frequently needed for problem and task clarification, and least frequently for concretising of solutions. Furthermore, the sketches serve as a support of real time communication and as an aided recall (Römer, Weißhahn, Hacker & Pache, 2001). The last named function becomes reasonable when considering that the fixing of innovative thoughts contributes to a relief of the working memory when sketching (cf. Ullman, Wood & Craig, 1990; Lawson, 1994; Pearson, Logie & Green, 1996; Purcell & Gero, 1998).

This could be confirmed experimentally for design requirements at which particularly analytical abilities were required during the event of handling problems (Sachse, 1999; 2002, 2006). The change between internal and external processing (during the event of problem handling) can lead to a relief of the mental processing capacity and the processing capacity itself and therefore to a reduction in the experienced use of mental resources of the person who is solving the problem.

Often the sketches as external stores still contain additional textual information in terms of abbreviated explanations (cf. figure 4).

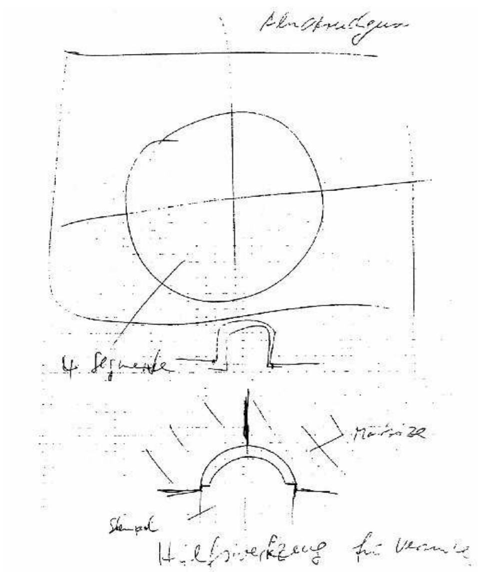

Figure 4: Sketch with abbreviated explanations (Collection Styner & Bienz AG, Niederwangen)

The combination of pictorial and abstract representations in a sketch with abbreviated explanations can increase the quality of expression, lead to the discovery of new meaningful connections, contribute to the further test planning and to the organisation of the design process. Such mixtures (multiple representations) can *reduce* the ambiguity (e.g. when choosing suitable problem-solving approaches) as well as *put into use* the ambiguity (e.g. when suggesting further associations) at the same time (Smith & Browne, 1993; Hacker, 1999).

On the one hand, the drawing of sketches concretises the solution representations and ideas; on the other hand, differentiation, control, and correction will be effected retroactively (Sachse, Hacker, Leinert & Riemer, 1999; Sachse, Hacker & Leinert, 2004). According to Görner (1994), the design sketch reflects not only the thinking result of the designer but rather primarily functions as working appliance.

During design processes, the process of sketching and its outcome, i.e. the sketch, has a considerably higher importance than the custom of just throwing the sketch away into the trash bin ("status problem"). Thus, the sketches cannot be used for further ideas and knowledge documentation: "The permanence of the sketch has perhaps been overlooked in favour of its spontaneity" (McGown, Green & Rodgers, 1998, 435).

Complicated design problems (e.g. at spatial penetration and adjustment problems, transform-technical requirements, adjustment of areas, and kinematical requirements) can often not be solely solved by sketching.

The more difficult the process of problem solving turns out to be, the *more definite* the object to be developed has to be illustrated. This can be carried out in the form of spatial, ***material models***.

Material models are not only a representational and developmental forms during the design process but at the same time also a suitable material creation for "experimenting".

If e.g. it is a question of fundamental functioning of a solution principle, orienting and developmental trials (hand trials) are often satisfying, which can be carried out for themselves in the design engineering department. These trials represent an approved and still necessary analysis technique with paper and wire frame models (figure 5).

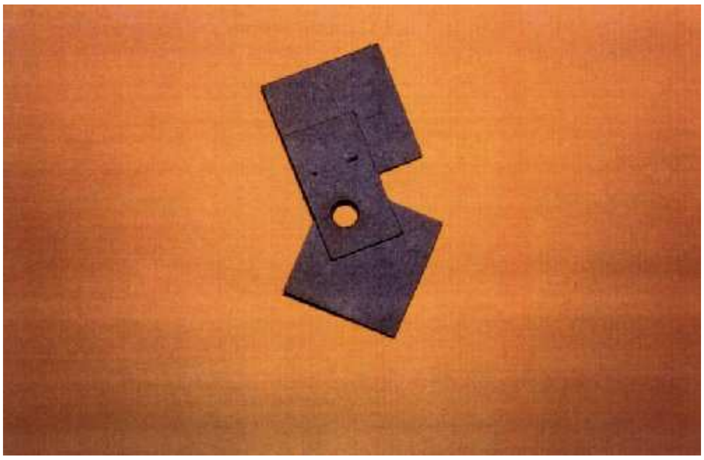

Figure 5: Simple and low-cost material model for hand trials (Collection Styner & Bienz AG, Niederwangen)

According to Radcliffe (1998), three different types of material models can be distinguished whilst taking into account their complexity:

a) *impromptu models*, to clarify first design ideas, to materialize manufacturing, to design easily respectively to express a design idea with directly available, tangible, and material everyday life ideas;

b) *proof-of-concept-models*, which, among others, serve the detailed representation and inspection of design concept, and

c) *embodiment models*, which already contain essential aspects of the structures, functionalities, etc. of the objects to be developed (products).

Supplementarily to the material models specifically created, also prefabricated, reusable components of material models are used in the design process. Among the latter little blocks, mechanics, or assembly boxes of building blocks are rated, for instance (see figure 6).

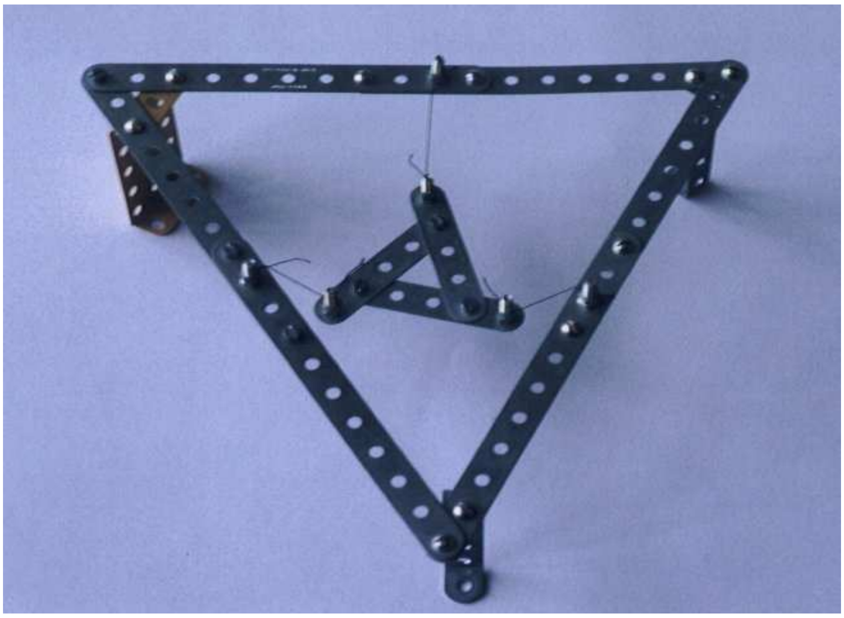

Figure 6: Material model, produced with elements of a montage construction kit
[Product development „Virtual Grippers“, Collection M. Sundin]

The production and use of material models is carried out in all phases of the design development, in which the low-cost models are used in the early phase of conceiving the development of problem-solving concepts as a matter of priority (Ehrenspiel, 1995; Sachse & Leinert, 1999; Sachse, 2002).

The material models also support the three-dimensional visualising during operating with complex technical structures and can serve as memory clearing, external knowledge-space at the same time.

Furthermore, Caroll, Thomas & Malhotra (1980) see the support value of material representation aids in an easier accessibility of information. “Modelling: A way of buying information” (Buur & Andreasen, 1989, 159).

Besides its memory clearing effect, modelling and its product, the model, also could support the process of solving a “design problem” due to the additional support during the design. Moreover, modelling as well as the model contribute to an organised thinking course and the chance of a successful processing increases (Leinert, Römer & Sachse, 1999; Römer, Leinert & Sachse, 2000; Sachse, Hacker & Leinert, 2004).

On the one hand, value of low-cost material models is generally (re-)acknowledged as necessary working respectively developmental means and as a support of technical design innovations. On the other hand, the potential of such models is still underestimated or even misjudged, and the application of modelling materials made out of paper, cardboard, modelling clay, etc. is accepted only reluctantly.

Only few enterprises still keep their relevant low-cost models after conclusion of product developments in order to retain the knowledge and to store it as possible idea contributors for new developments.

The storage is carried out almost exclusively by selected high-tech prototypes. These prototypes are only the developmental result, however, and do not provide information about the process of solution.

The ignoring of necessary sketching and modelling can lead to difficulties regarding a successful course of design engineering, which relates to mental problems, task representations, and mental operations. Furthermore, it can come to a stagnation of the developing ability to solve problems along with impairments concerning the gain of experience and learning (table 1).

Table 1: Impairments by neglect of sketching and modelling (Sachse & Leinert, 1999)

Impairments	
regarding the tasks and problem representation	• Deprivation of the bases of sensory perception • Aggravated construction of mental models • Action requirements, which go beyond one's own knowledge • Disregarding of designing engineer's practical experience • Restricted development of a procedure plan
regarding the thinking and problem solving	• Hinderance of the problem solving process • Impairment of the creative procedure • Appearance of cognitive emergency operations (ad-hoc-decisions, analysis renunciation) • More time-consuming, aggravated solution finding
regarding the gain of learning / experience	• Loss of a comprehensive participation in the developmental process • Obstruction of learning processes

Sketches, material models, and prototypes have several general basic functions for the designer within the developmental process: They serve as the generalisation of complex design facts and the various connections (working structures), planning, control, as well as the reflection. Further, the systematic interview of professionally experienced designers done by us showed that the different external support manners could act as analysis, solution finding, assessment, storage, and communication aids (Sachse & Hacker, 1997; Sachse, 2002; Hacker & Sachse, 2006).

The sketches and material models are aids for the appropriation of creative modes of operation and also vivid thinking and action. They are a medium of the externalisation of the rehearsal action performed at mental “models”. The mental processes are enhanced by external operations.

It is decisive that thought-processes and practical behaviour are not separated but rather entangled because recognising takes place by the practical action.

Without the “thinking actions” of the hands we would literally lose an essential part of the human thinking. Therefore, even philosophical puns may be *grasped* and hence not so fast rejected out of hand: *“I know that I have two hands”* … *“For I have two hands, I know”* (Moore, modified of Gebauer, 1984, p. 246).

Are the manual sketching / modelling and the use of current digital means of work (e.g. CAD) completely contrasting? Certainly not! The support forms contrasting at a first glance can complement each other effectively, which current experimental results prove (figure 7).

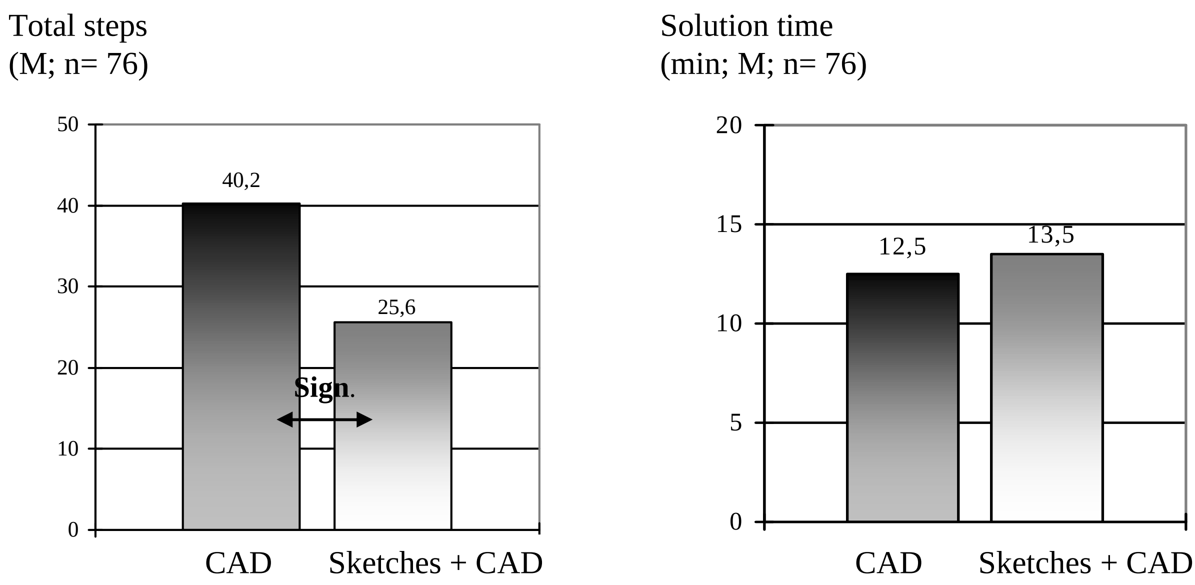

Figure 7: Construction of a drive device (Sachse, Leinert & Hacker, 2001)

The number of required solution steps towards the construction of a drive device able to work was reduced significantly when using a composite support form (early sketches + CAD) compared to a processing exclusively CAD-supported.

Despite the additional time exposure of on an average 30% of the total production time for sketching, the processing and solution time, however, did not prolong itself significantly. An offer of assistance which shall cover all functions and processing phases (see above) must combine simple and complex, analogous, and digital support forms as a basic recommendation to a ***"mixed prototyping"***. Thus, on the one hand, early and low-cost supporting of the creative early phases (early low-cost rapid prototyping) and, on the other hand, a comprehensive support of phases and functions will be possible.

With *preparatory* sketches the CAD work is planned ahead and organised. Moreover, CAD specific information, e.g. coordinate details, is recorded in the sketches, since the CAD systems usually require it when entering geometry data (figure 8).

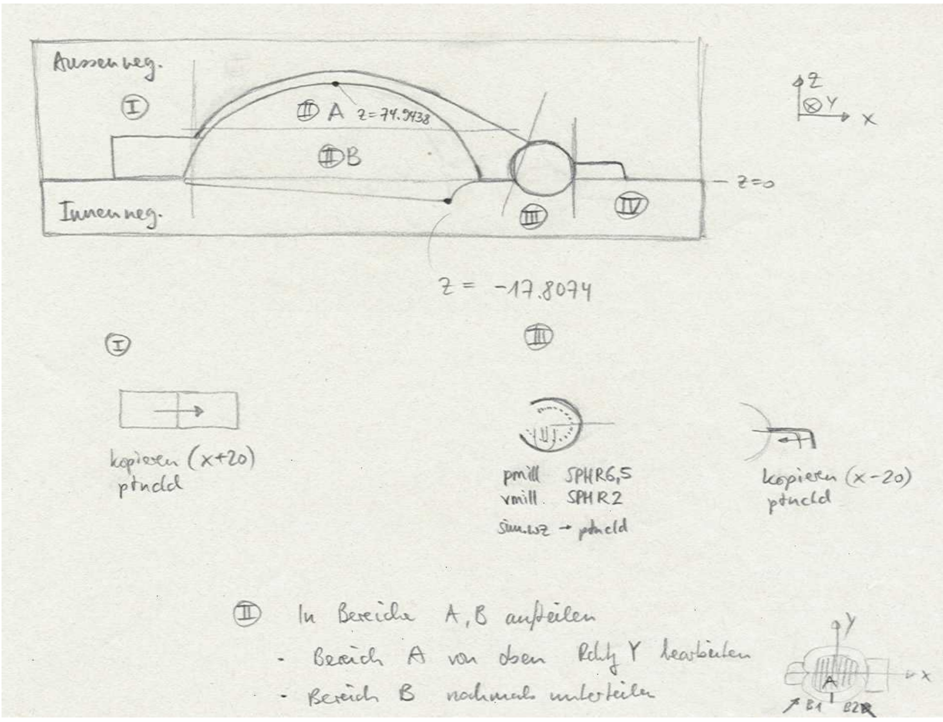

Figure 8: Preliminary sketch with CAD-specific information (according to R. Zanini)

Due to the lack of precise information concerning the still vague solution variants of the early design phases, “an efficient use of the computer becomes impossible when sketching in the concept phase” (Rückert, 1997, p. 152). Notwithstanding, CAD systems are also used in these phases on a considerable scale. The mere retaining of the coordinates of single elements leads to an extraordinary load for the working memory. However, the relief of the working memory should be the real aim of the computer aid.

The criticism levelled at the currently common CAD systems by professionally experienced designers and engineering scientists is fundamental and far-reaching:

- “There are only few overlaps between that what design software is capable of doing and what runs off in the reality when designing. The users are overextended by the amount of the data and the way of the input.”
- “Present CAD-systems have got nearly nothing in common with the thinking processes and approaches being made when designing.”
- “To save a picture or a thought in the computer, the designer has to give not quite a small share of his mental capacity to the device.”
- “During work with 3D-CAD, the system control operation ’slows down’ and impedes the idea flow and the development of the solution.”

Further objections concerning CAD applications are based on the dominance of the visualisation to the account of haptic perception, acoustics, etc; furthermore, a lack of experienceable, concrete action and the neglect of the implicit (i.e. not digitalising) experience knowledge can be observed.

Quo vadis, CAD? Tangible CAD (TCAD) shall not replace but complete the classic CAD. TCAD consists of a mini-CAD/CAM system, a circular table to spread the models out, a visual measurement system (Atos) for the form capture and a robot for a subtractive and additive processing. The user of a TCAD has both the information regarding the processed material model and the CAD data. Changes can be applied by means of CAD or directly at the material model. If the designer changes the material model manually, TCAD updates the CAD data automatically.

3 Knowledge-based and "opportunistic" development of the solution

Working on and solving sketching problems combines the use of knowledge regarding already known solutions and the conceiving of new solution methods. Thus, the designing process is not just a systematic, target-oriented, continuous execution of a drawn up process plan and working out of solutions but rather a process in the sense of the conception of an “opportunistic” problem solving (Hayes-Roth & Hayes-Roth, 1979) respectively “resulting opportunities” (Visser, 1994). Newly discovered knowledge which can be used to solve a given problem is gradually integrated into the process of solution. One could imagine those incoherent information bits as disconnected “knowledge isles” which have to be integrated and reorganised by “skipping from knowledge isle to knowledge isle” within the design process in order to establish a whole “knowledge landscape” out of the single “knowledge isles” standing initially alone. The discovered knowledge during the process of solution finding can induce the designer to reconsider the particular “design problem” again and to change the procedure plan if required. With the further solution progress, the previously required reentries should be reduced to already finished phases. Moreover, the “jumps forward” should be reduced in periods not yet processed. A systematic handling will be only possible after an elemental breakdown of the “design problems” into different “problem branches” with a flexibly target-oriented approach within the process of problem analysing. The assumption of a systematically hierarchical procedure (stating that “design problems” are being decompounded from, starting from a rough concept and ending with elaborate details) contradicts several empirical results. The reason therefore is due to the “principle of cognitive ecology” among others, according to which “opportunities” to proceed cognitive-economically can either be purposefully sought after or desultorily gathered. Systematically “decompounding” of a “design problem” charges one’s working memory considerably. For this reason, hierarchical decomposition strategies are also avoided in further task classes. Furthermore, it could be proved that subjects with a lower working memory capacity take more unnecessary steps while designing; also, they show particular deficits in procedure and results when not sketching (see figure 9).

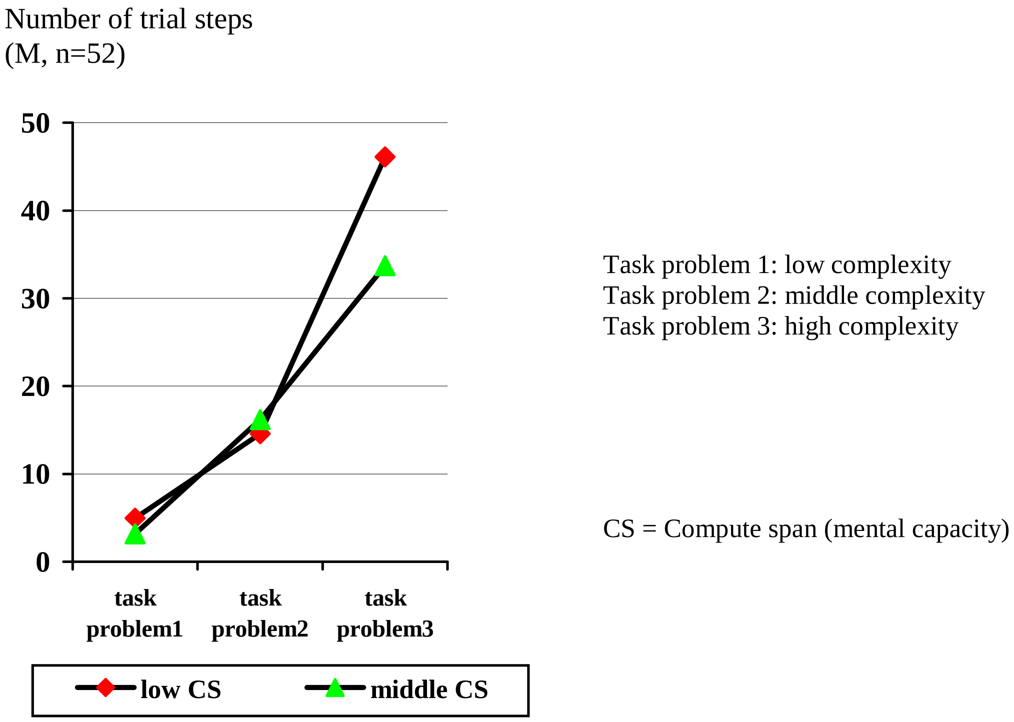

Figure 9: Investigation of design problems in practice (Experimental results)

Summarising, the individual features of the "opportunistic" procedure can be described as follows (Hacker, Sachse & von der Weth, 1996; Hacker, 2005; Hacker & Sachse, 2006):

- There is an irregular change between mental and external routine, e.g. during graphic clarification tests of problem partitions.
- Before going over to designing, problems are not completely and systematically analysed and the understanding of a problem is not yet complete during the initial transitions to processing.
- The irregular changes of the problem areas and the abstraction levels of their processing are caused by experience supported discovering of knowledge which may lead to solutions.
- The discovered knowledge respectively the newly gained insights cause a reformulation of the problems and changes in the procedure plan.

An adequate external support of mental processes particularly in the important early phases of the design process must take into account the "opportunistic" initial steps and the possible support forms should be adapted to the "opportunistic" behaviour.

4 Knowledge retention

An example: The leaders of the engineering area of a mechanical engineering enterprise spotted that the enterprise had an exceptionally extensive company know-how. This knowledge, however, is only collected partially and of what was collected only a small bit was actually used. Solutions were sought after to slow down the wasting of company knowledge. Hence, for instance, all sketches and material models are being collected as external knowledge stores (also for the design solutions not carried out) in this enterprise now. To be able to find these and all additional documents quickly, every designer writes down his solution approach and the accrued documents on a so-called “design process map” (Schroda & Sachse, 2000; Hacker & Sachse, 2006). The design process or knowledge map illustrates the development. The main part of the work steps of the design activity were taken into account in terms of a design guide in the design process map without providing an algorithmic order. Moreover, individual and problem-specific steps can also be added. Furthermore, external offers of assistance which take into account the adequate point in time of application of a tool and its particular function are noted down in this map as well. The design process map contains methodical, pictorial/concrete, and verbal/numeric support forms.

The design process map supports the

- *Planning the design process* – the map structures the process, supports the project management, serves the progress control and contributes to the planning reliability. One can also plan backwards with this method.
- *Documentation of the design process* – the knowledge of actions difficult to verbalise becomes easily and partially indirectly visible and hence it may be expressed by communication. Further, the user-friendly documentation of the design process with the map serves the knowledge management. The often elusive design process becomes transparent.
- *Self reflection on the design process* – by the pictorial and holistic illustration of the design process using the map, one’s own actions are permanently fed back and therefore functions as a stimulus to self reflection. With immediate feedback, the map also serves as a “learning map” (process optimisation). The map is a meta-plan and communication basis when used in a team.

The design process map as a knowledge map is a vividly designed key to searching in the digital stores of the mechanical engineering enterprise. However, such modern databases as external stores are only used if the searching time is considerably less than the time for a new-conceiving and the finding probability is high. This means that one should consider when gathering information and integrating it into knowledge maps under which search terms and in which contexts someone ought to search for that information in the future. However, if information is not retraceable, it is regarded as lost. When choosing the external (digitalised) stores, it must be taken into account that they do not make higher demands on the working memory than they are actually capable of reducing.

5 Conclusion

The research regarding the "Embodied knowledge in design" is still in its beginnings compared to other research areas. Despite the extraordinary economic meaning of its possible results, it finds little support. This has to do with its interdisciplinary character amongst others: This research field concerns different disciplines as a cognition psychological and work psychological research as well as a technology scientific research without representing a central topic in one of these disciplines, however. Yet international working groups gradually develop from which an amplified and coordinated continuation of the research lines already started may be expected.

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