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EXTRACTION OF CAD TOOL REQUIREMENTS FROM INDUSTRY AND FROM EXPERIMENTAL DESIGN PROJECTS

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ABSTRACT

In spite of the advances of current CAD systems, the conceptual phases of design still suffer from lack of appropriate support tools. Contemporary research toward design support and automation puts substantial effort into the development of improved Computer-Aided Conceptual Design (CACD) and Computer-Aided Industrial Design (CAID) systems, both by industrial R&D and by science academia. However, there are indications that some of the persistent problems can only be solved if we more deeply understand what the requirements for the tools are. We extracted these requirements from two sources, from practicing designers in industry based on an inquiry, and from data generated in experimental design processes.

The inquiry indicated that improved CAD tools for conceptual design were lacking and would be welcomed if they were available. It was also explicitly revealed that even in the earliest phase of conceptual design, the enforcing of constraints to the designed shape was rated as crucial, besides an unlimited freedom of shape modeling as, *e.g.* offered by virtual claying. In general, a computer-based, early evaluation and analysis of design alternatives was ranked as the most urgent type of tool that should be developed.

Analysis of the protocol data from the design experiments revealed two items. First, the technical quality of the designs obtained by the test subjects suffered from a lack of intermediate evaluation. Second, the subjects often neglected to utilize an evaluation tool when it was provided.

From the extracted requirements we were able to derive recommendations for the research into better CACD tools. We also present some recent results that we obtained when we followed the recommendations.

INTRODUCTION

Design automation is a controversial issue among conceptual designers and stylists. On the one hand, new tools dedicated to industrial design (CAID) and conceptual design (CACD) are becoming indispensable for certain stages of product design; on the other hand there remain tasks of product conception and styling design where computer tools are either not accepted or proved counterproductive, or both (Tovey 1997). Products designed in industry become more and more complex and product liability urges designers to take into account all sorts of possible (and impossible) use (Hales, 1998). Furthermore the time-to-market plays an important role in the profit prospects of a company (as has been confirmed by the inquiry, presented in this paper). The conceptual design of new products is often a complex task and it should benefit from computer support where possible. The incorporation of support means can be done by applying ready-made tools, or by developing dedicated tools. From the company's angle, the first method seems the easiest. Costs are limited to the purchase and introduction of new methods. The development of new tools involves much more, *e.g.* requirements engineering, prototyping, implementation and evaluation. Current CAD tools turn out to fit not adequately to the activities of conceptual design. Therefore, further study of the user's requirements and the exploration of new methods of design automation and supporting tools is of crucial importance. Both the R&D in industry and academic researchers are working towards improved design tools. However, there appears to be a severe issue concerning the interplay between academic research and the concrete needs of designers in industry (Reich 1995). A recent survey (Handenhoven 1999) in France of small and medium enterprises revealed that the majority of these companies declared that they do not use any academic method or procedure in the design stage, except from CAD/CAM for detailed design.

The proliferation of CAD in the conceptual design and styling departments is significant but far from what could be expected, considering the almost unlimited flexibility and freedom that recent modelers provide to the user. Gaining understanding of this apparent mismatch was also our motivation to explore the user's requirements more deeply. Besides attempting to solve the problem of effective computer support of conceptual design, the communication between practicing engineers and academic research projects should be addressed as well. This might help to increase the chance that the technical requirements for the tools are the ones that should actually be fulfilled. Hence the following problems need to be addressed:

1. How should conceptual design tool requirements be obtained, and from whom?
2. How can these requirements be interpreted and be verified?
3. How can these requirements be met?

In some research, the latter problem actually forms the starting point of a project, rather than a proven or tested condition. We report initial results of a research into new conceptual design tools, in which all three stages are comprised. However, the main emphasis of this paper is on the first stage, the extraction of authentic requirements. The verification of requirements is also addressed.

We used two sources of information for design tool requirements, statements made by practicing designers in industry and observations of test subjects performing a controlled design process. Concerning the test persons we need to account for their possible experience with existing tools. A challenging issue was to reduce the influence of such experience on the opinion and actions of the persons we approached. For we did not want to know how existing tools should be improved, but rather which functionality (either or not feasible) needs to be put in place.

EXTRACTION OF TOOL REQUIREMENTS FROM COMPANIES

The most direct way to identify the requirements of better design tools is the inquiry of the users working in the industry. They can be either the users of present systems, or designers and engineers that would potentially use a proposed, better, but not yet existing tool. Typically, the first group of users will put forward gradual improvements of the systems they already use, whereas the second group may come up with extravagant speculations about what a conceptual design system should be capable of. To obtain data that is useful as an input to developers and researchers of new tools, it is important to find a right balance between those extremes.

In this section we report on an inquiry among professional engineers and product developers. We focused on one aspect of design, namely shape conceptualization. This choice was motivated by the supposition that the geometric shape of a product, although by no means the exclusive aspect of interest, plays a central role in the conceptualization phase and during the entire lifetime of the design and the realized product. Nevertheless, this conjecture was explicitly evaluated during the inquiries.

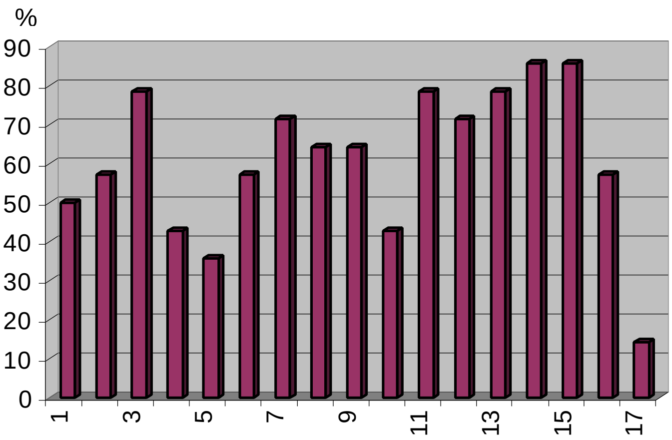
The aim of the inquiry was to obtain input to the research into new computer-based design tools, as presently conducted in the ICA project at the Delft University of Technology. One of the issues studied is concerned with the apparent shortcomings of even the most recent shape design tools. It is sometimes stated that the user should have unlimited freedom when manipulating the object's shape. This is seemingly what is offered to the user in the form of unlimited pick-and-drag of any point or region on its shape. However, we hypothesize that unlimited shape editing can be far from effective, and that constraints into these processes should be introduced, even in the earliest stage of shape conceptualization. The inquiry was meant to explicitly reveal these types of issues.

The inquiry does not provide a statistics-based account of any design/engineering factor in industry. We were looking for some typical, practical situations in a company that would pinpoint the issue of lacking computer support in conceptual shape design. The companies that we approached do not necessarily form a representative subset.

We asked engineers and designers from 22 enterprises to provide a realistic description of a shape conceptualization process as it typically occurs in the company. For each case we inquired how relevant shape conceptualization was, for the company in general and for the specific design process that was mentioned. Then the respondent was asked to supply detail about the depicted shape conceptualization process. A questionnaire was used to enter data about these processes. We also asked to which extent computer support was applied and whether or not the introduction of existing or hypothetical tools might have made the process more efficient or more effective. Also the perceived shortcomings of the shape design process and/or actions associated to it where investigated.

Results from the inquiry

The response rate to the questionnaire was 68% (15 out of 22). Compared to other written inquiries this is a very high response rate. Rather than approaching companies using bulk mailing we contacted responsible engineers by telephone or e-mail first and asked for their agreement to accepting the questionnaire. The questionnaires were sent only to those companies that reacted positively. Each of the respondents was either a practicing stylist or design engineer, or was directly responsible for a design department. Most of the respondents were involved in a multitude of tasks (see figure 1), but invariably, each of them was directly connected to the design of shape of new products. The companies were all located in the Netherlands and ranged in size from one-man's offices till multinational enterprises.



1. Market research
2. New product specification
3. Generating product concepts
4. Product aspects
5. Product parts
6. Global shape specification
7. Generation of shape concepts
8. Paper sketching
9. 2D CAD
10. 3D physical
11. 3D CAD
12. Shape evaluation
13. Shape modification
14. Shape modification using cad
15. CAD model exchange
16. Providing feedback to design/styling
17. Any other

Figure 1. Fraction of the respondents that were involved in the different tasks.

For a full analysis of the returned questionnaires we refer to (van 't Riet, 2000). In this paper we only highlight the findings that are most relevant to the extraction of tool requirements. The important outcomes of the analysis are:

1) In 87% of the investigated companies, the product's shape is either of dominant importance (40%) or at least as important as other engineering aspects (47%). However, 100% of the respondents remarked that shape is not the exclusive concern.

2) Only 15% of the respondents claim that conceptual shape design does not pose a significant problem.

3) We asked the designers which activities of the process of shape development needs improved support most urgently. 40% of the respondent mentioned the initial input of shape, and 45% shape modification with some form of feedback from manufacturing or other parties.

4) The aspect of shape development most frequently indicated (24%) as the one that lacks computer support was "manufacturability" in conjunction with some sort of easy shape control or shape parameterization (see figure 2). 24% of the respondents mentioned shape evaluation and analysis of some type as the most important aspect that should be better supported (6% form/aesthetics, 12% virtual prototyping, 6% analysis). More general aspects including "A good CAD/CAM system" (18%) and "cost, speed, quality" (24%) were mentioned as well.

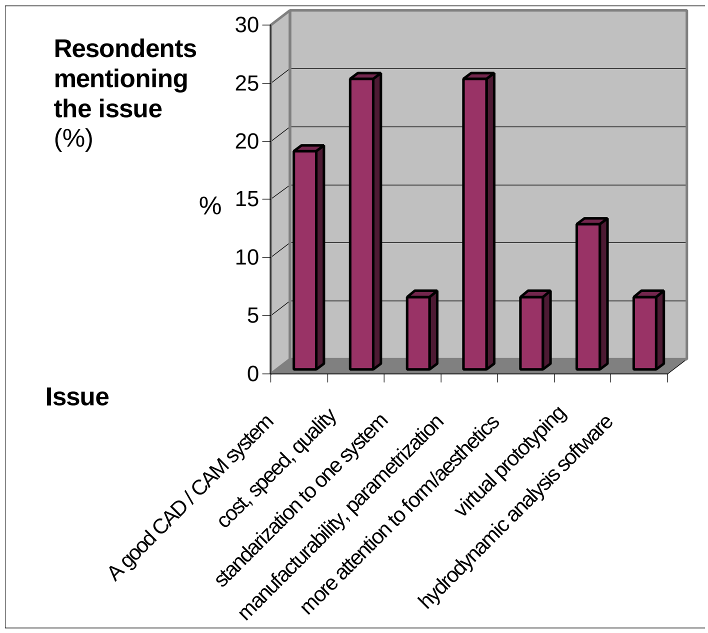


Figure 2. Issues in the shape conceptualization process which need improvement most urgently.

Each respondent provided a description of a shape design engineering process as it typically occurred within the company. It turned out that only 27% of the initial shapes were obtained from numerical data. In the remaining 73% of the described projects, some form of pencil sketching or physical clay modeling occurred first. However, in 93% of the cases, a computer-based model was required as output from the design department. Therefore, in the majority of the conceptual shape design processes, a transition from traditional to electronic representation form takes place.

Conclusion from the inquiry

From the questionnaires a number of technical issues concerning CAD support for conceptual shape design could be clarified in an explicit way. Some of these issues are being addressed by research in the ICA group; voice control and behavioral shape modeling are example topics. One of the most salient outcomes from the investigation is the strong need for immediate control of the shape, *however under certain constraints*. The character of these constraints differs among the different process descriptions; they originate from manufacturing, styling or functional requirements.

This touches a fundamental issue in design automation, the trade-off between the offering of tools for free and fast creation of shape alternatives on one hand, and on the other hand setting and maintaining constraints to the shapes. The challenge, obviously, is to dynamically ascertain which constraints should and which ones should not be applied to the designed shape. The ultimate shape design tool should have that capability. Some of the respondents even explicitly declared that they needed a tool to manipulate parameterizable shapes, where manufacturing constraints were implemented into the parameterization. This functionality is offered by feature-based CAD/CAM systems, but in the domain of regular shapes only, not for freeform shapes (Eversheim 2000).

EXTRACTION OF TOOL REQUIREMENTS FROM EXPERIMENTAL DESIGN PROCESSES

Experimental design processes have been studied in various ways and for many different purposes (Stauffer 1988, Blessing 1995, Dörner 1998). Most of the research methods involved video taping of the designer's actions, utterances, drawings etc., followed by some form of protocol analysis. If the purpose of the experiments is to assess the needs for and/or the effectiveness of a supporting tool, then a criterion should be available against which the goodness of design (or design performance) can be measured. However, we found only few reports in the literature about measuring the effectiveness of a new method or tool in a given type of design process (Blessing, 1994, Wiegers 1998). In the following we describe:

- The design experiment and method of observation and data acquisition,
- The method used to assign a rating to each design process,
- The data obtained from the experiments and their interpretation,
- Attempts to measure the influence of simulated design tool on the rating of the design process.

Setup of the design experiment

In the first stage of the experiment we recorded 10 independent sessions, where in each session a subject worked about two and a half hours on a mechanical/electrical problem. The protocol data was transcribed into computer readable form. The analysis was based on this data and on the design documents produced by the 10 subjects (Van Bremen 1996). The engineering assignment in this experiment involved the conception and technical specification of an alternative electrical lighting system for a new type of bicycle. Ten technical requirements were mentioned in the assignment, and the subject was asked to explicitly show that the proposed design could meet those requirements. Since the maximal duration of the session was fixed to 160 minutes, several restrictions were built in to avoid that much time was spent on making too detailed descriptions or illustrations. The technical and functional aspects were emphasized. Two of the designed concepts are shown in Figures 3.

The subjects, all near-graduate engineering design students, worked on this assignment independently. In advance each subject was asked to work on a smaller assignment, to let him or her get used to the working environment. Before and after the session each subject was interviewed following a list of questions. All subjects declared that they did not feel hampered in any way during their engineering task.

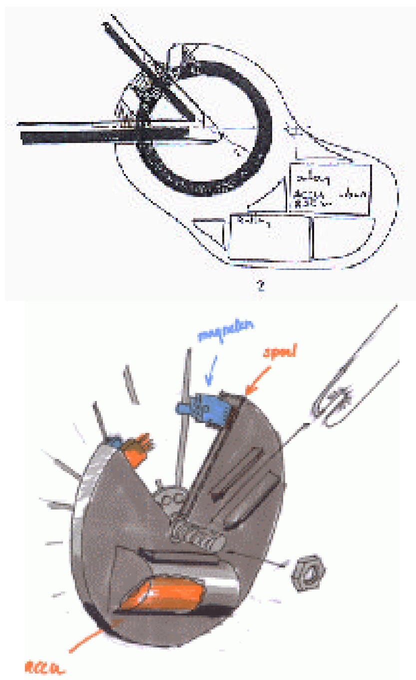


Figure 3. Two of the designed concepts for a bicycle lighting system.

To capture the data it was not necessary to let the subject think aloud, as is done in some protocol studies. Instead, the subjects were encouraged to speak only if they had a new information request and/or started a new activity. In addition, at regular time intervals during the session a clock signal reminded the subject to briefly mention his or her current activity and any need for information. For this experiment the time interval was set to 5 minutes. Information requests were handled by an experimenter located near the subject's desk. The experimenter had a set of general technical documentation and some specimen available, and was well prepared to accept questions about the assignment. The role of the experimenter was deliberately restricted to providing simple answers; no advises, hints or judgements about the design itself were given. All questions, answers, activities and results (either pronounced or directly observable) were listed during the session by a second experimenter, watching the session on a video monitor, in a separate room. After the session, the drawings and texts produced by the subject were merged with the list. Then, following a well-defined procedure, it was determined which activities were continuations of previous similar activities. This led to the identification of activities and subactivities, discussed further below. Also a search was made for information links, defined as explicit uses of earlier results (Knoop 1996).

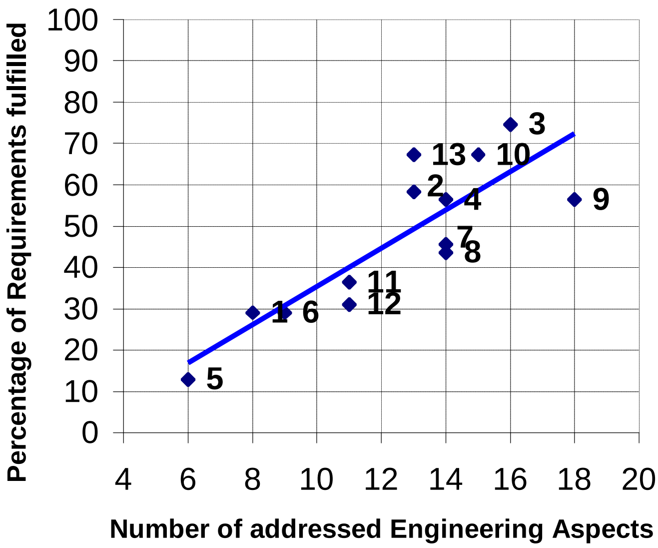


Figure 4. The percentage of requirements that are fulfilled, plotted against the number of addressed Engineering Aspects.

Analysis of the experimental data

The data was used to visualize and analyze activities, information requests and design performance as a function of time, and to statistically correlate the quantities (Vergeest 1995, van Breemen 1996a, Wiegers 1997). The value of a design process was rated based on an independent judgement by an expert, who determined which of the technical requirements were addressed and met in the design concept. The rating was defined as the fraction of the engineering requirements met by the design as documented by the subject.

An expert was given the assignment and asked to list all engineering aspects that should have been taken into account to solve the problem. These aspects concerned for example the bicycle's rear axle, generator types, lighting consumption and the energy that the cyclist must deliver. There was a large variation of the number of engineering aspects addressed by the subjects. Previous investigations indicated a correlation between the number of addressed engineering aspects and the rating obtained for the design concept (Wiegers 1996). Figure 4 displays the ratings obtained by the 10 subjects in the first stage of the experiment. The data of subjects 11, 12 and 13 from the second experiment (described later) are also included in the plot. Qualitative analysis of the data revealed the following types of bottlenecks in the design processes:

1. *Unawareness of errors* that are made and postponement of evaluation Subjects generally spent much time on working out a part of a design that contained a fundamental error.
2. *No recording of design information*. Subjects were different in the style in which they recorded generated information (e.g. found values, concepts and ideas). We saw some subjects invent solutions they had already found before, however without registering them. In other situations sketches were used to record significant information.
3. No use of "prototype concepts" *to explore the problem* and to evaluate possible solutions. Sketching often helped subjects to get more insight in the design problem. Some subjects generated a number of concepts from which they selected the most appropriate one. During the generation of the later concepts, they often applied knowledge that they had gained from the earlier concepts. Sometimes subjects made assumptions on values and solution structures to be able to generate a rapid model of the design problem, a sort of prototype concept.
4. *Information overload* and the necessity to keep track of open problems. After receiving new information, subjects immediately tried to apply it. If a large amount of new information was received, often subjects did not generate new results for a long time. We observed that subjects tend to remain idle awaiting the answer to a question they asked the experimenter.
5. *Lack of domain knowledge*. Many subjects suffered from lack of domain knowledge. They had difficulties within the following domains:
   - The generation of electricity
   - Charging and discharging batteries
   - The energy balance and the effect of energy losses

– The construction and geometry of a bicycle rear wheel

Many designs did not work because of errors in these domains. Moreover, subjects spent so much time on aspects in these domains, that they neglected other important aspects. The subjects did not easily make assumptions for values or solutions in a domain they were not familiar with. Instead of making an assumption, they tried to clarify all the details before they paid attention to other aspects of the design.

6. *Lack of orientation.* Subjects were different in their estimation of the importance of aspects. Often, they were even not aware of the basic, underlying problem of the design assignment. During the design sessions, at regular time intervals the experimenter asked the subject to briefly express her or his current activity, results, and needs for information. Eight times the experimentors' questions elicited utterings about activities and results that subjects did not yet express before, on their own initiatives. From the results the subjects reported, 7% was mentioned after a request of the experimenter. Twelve times a subject took a decision and closed the current activity right after such an answer.

Potential design support methods

The 6 types of bottlenecks listed above might suggest which tools (or any other sort of intervention) could have improved the design processes. The problem here, of course, is how to prove that the inclusion of a tool actually brings improvement. Being fully aware of this concern, we provisionally defined improvement as 1) a decrease of the number of bottlenecks observed in the data and 2) an increase of the rating of the resulting design concept. A possible method to detect any such improvement is described in the next subsection.

First we searched for types of intervention that could have improved the design processes. The analysis of the 10 design processes with regard to the six types of bottlenecks yielded information about unnecessary delays, easily-to-avoid errors, total neglect of assigned requirements and failing to consider alternative solutions (Wiegers 2001). From the video tapes, the protocols and the formal diagrams of the sessions, the following interventions seemed the most needed:

1. Make designers early aware of errors they make and avoid postponement of evaluation,
2. Encourage the recording of design information for later reference,
3. Encourage the use of "prototype concepts" to explore engineering issues and to evaluate possible solutions,
4. Avoid information overload and automate the administration of open problems,
5. Provide domain knowledge, but only if and as needed
6. Help designers to be aware of their current activity and its contribution to the design process as a whole

These findings are in accord with results from most other design studies and protocol analyses.

Inclusion of a design tool

To test whether any of the 6 types of intervention could have an effect on the data, we focused on the first item listed above (early evaluation of the design), for further investigation. The test was conducted as follows. We ran 3 new sessions of the same design process, with new subjects, where the only difference was that the subjects had a design assessment "tool" to their disposal. This tool was, for the purpose of the investigation, simulated by an experimenter. We refer to this tool as the assessment tool (AT) from here on. Before the subjects began their session, they were instructed to make use of the AT at any time they liked. To ask for an assessment, the subject had to enter the necessary data about the design concept into an assessment request form on paper and hand it over to the AT. This form was the only information that AT got about the ongoing session. The result of the assessment delivered by AT could be only one of:

- 'Yes' if the concept met the mentioned requirement,

- 'No' if the concept did not meet the mentioned requirement,
- 'Insufficient information' if the description on the assessment form was not sufficient to evaluate the concept.

Typically, the response time of AT was between 1 and 2 minutes.

The influence of the tool

One of the most remarkable outcomes of the 3 sessions (by subjects *S*11, *S*12 and *S*13) was that the tool AT was actually used in session 13 only and was totally neglected by the remaining two subjects.

*S*13 applied the assessment forms three times. The first time was to verify whether the generator output power was sufficient. The output power appeared to be too low. Because of this, *S13* stopped recalculating his figures and started to look for a way to deliver more power. With the second assessment form, *S*13 wanted to verify the required minimal efficiency. The answer on his request was that the concept contains insufficient data for the requested assessment. *S*13 did not reject the concept and searched for more specific information on generators. The third time, after *S*13 decided to purchase the inner part of the AXA generator, AT confirmed that the design concept was feasible. In all three cases, *S*13 made a major design decision after the assessment. The ratings obtained by *S*11, *S*12 and *S*13 were 36%, 31% and 67%, respectively.

Preliminary interpretation

The experimental design projects supplied detailed information about six types of deficiencies in the processes. To improve with regard to one of these deficiencies (lack of early evaluation) we have proposed the assessment tool, simulated by a human expert. Only one out of three subjects took the opportunity to utilize the tool during the session. Qualitative analysis of session 13 revealed that it contained relatively few bottlenecks. The rating (67%) obtained by the subject that used the tool was the second highest obtained by any of the 13 subjects. Figure 4 shows that no subject scored a higher rating while addressing fewer engineering aspects than did *S*13. To demonstrate statistically that the tool increases the rating would, obviously, require the execution of many more design sessions and careful interpretation.

CONCLUSIONS AND ONGOING RESEARCH

We acquired user requirements of CAD tools from two sources, from industrial users and from experimental design processes. A common denominator among all data was the need of a supporting tool to evaluate the design concept at the earliest possible time. Stylists and designers often mentioned the need for unlimited freedom (*e.g.* virtual shape claying) but at the same time expected a continuous verification of the shape against a number of constraints (*e.g.* from manufacturing or being inherent to the part's functionality). These tool requirements seem almost contradicting, although they may actually pinpoint at a key issue in design automation, namely the balance between algorithmic processing and level of interaction with the user. This dilemma is visible in the design experimental data too. Early evaluation was clearly overlooked by many of the subjects. However, when an evaluation tool was offered, it was rarely used, although the design quality could have been improved when the tool were used. This hypothesis might be tested by *enforcing* the subjects to use the tool at a number of times during the session. But imposing the use of tools might limit the freedom of the conceptual designer.

In some of our earlier work we addressed this problem by explicitly involving the end-users in the research of new CAD tools (van Elsas 1998, Vergeest 1996). Both the effectiveness and the acceptability of a new high-level shape-modelling tool could thus be successfully tested. Another approach is to test new CAD tools prior to any software implementation, as was performed by (Dijk 1998) and more recently by (Opiyo 2000).

Further work is needed into the development of an improved research methodology, to extract, analyse and validate requirements for new conceptual design tools. These phases are at least as important as the further technical development of the tool itself. Obviously, also during the development and implementation of the tool, the end user should remain involved constantly.

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