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# Use of models in conceptual design

G. MAARTEN BONNEMA* and FRED J. A. M. VAN HOUTEN

University of Twente, The Netherlands

This article investigates the use of product models by conceptual designers. After a short introduction, abstraction applied in conceptual design is described. A model that places conceptual design in a three-dimensional space is used. Applications of conceptual design from the literature are used to identify several product models used by conceptual designers to handle the complex problems. Next, the models available in four conceptual design support tools are listed. In order to investigate the current use of models by conceptual designers, a questionnaire has been designed and issued. The design and results of this questionnaire are described and analysed. The results have been discussed with conceptual designers. It is concluded that several types of models are needed for conceptual designers to cope with and structure the large amount of information. In particular, budgets are used in the very early stages of the design process. Following that, mathematical models, physical models, block diagrams, specifications, and sketches are used. computer-aided design tools are used to implement the design. Finally, steps for further research are given.

*Keywords*: Conceptual design; Models; Interviews; Multidisciplinary cooperation; High tech system; System development

## 1. Introduction

Many words have been written about the design process (French 1985, Pahl and Beitz 1996, Horváth 2000 and references contained therein). It is generally accepted that the early part of the design process, the conceptual phase, is relatively inexpensive. The group of people is small, and the materials required are simple and for general purpose. However, the most important decisions are made in that early part, thus defining the cost of the product to a very large extent (Lennings *et al.* 2000). Therefore it is paramount that the decisions taken in this phase are rigidly founded on firm arguments.

Michael French (1985) states about conceptual design:

> It is the phase where engineering science, practical knowledge, production methods, and commercial aspects need to be brought together, and where the most important decisions are taken.
>
> (p. 3)

Thus, a huge amount of information from different fields of science has to be handled.

One part of the research at the Laboratory for Design, Production and Management at the Department of Engineering Technology of the University of Twente is to investigate the possibilities for a support tool for the conceptual design phase.

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*Corresponding author. Email: g.m.bonnema@utwente.nl

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It is expected that models play an important role in the work of conceptual designers. This article will look into this by making an inventory of models used, organizing them using a model of conceptual design in literature and selecting a set of models that covers the conceptual phase. The results will be used in the development of the conceptual design support tool.

First, a short introduction on the conceptual design phase is given, followed by a list of models from the literature on conceptual design projects and from models used by computer support tools for conceptual design. Section 4 covers the design of a questionnaire to make an inventory of the models used by conceptual designers. The section also contains the results. The results will be further discussed in section 5. Section 6 describes the outcome of interviews with conceptual designers on the results. In sections 7 and 8, the conclusions and plans for future work will be presented, respectively.

## 2. Conceptual design

In Krumhauer (1974) an interesting model for the conceptual design phase is given (see figure 1). The route from problem to solution is placed in a three-dimensional space, defined by the axes *complexity*, *concreteness* and *realization*. The problem that is complex and concrete, but is not yet realized, is dealt with by first abstracting (reduce concreteness) and then splitting into subproblems (reduce complexity). These subproblems can then be solved, thus increasing the realization and concreteness. By assembling the subproblems into a complete system, the complexity is increased. Where the start of the design process is concrete and complex but not yet realized, the solution is complex, concrete and realized. Important instruments are thus abstraction and splitting into subproblems.

Abstraction is also mentioned in Kao and Archer (1997), where several designers have been observed during a not too complicated design case. Three types of abstraction are identified: *horizontal*, *vertical* and *general*. Horizontal relates to complexity in the model in figure 1 and vertical to concreteness, whereas general abstraction is not directly linked to the model by Krumhauer. It is described as a combination of horizontal and vertical abstraction to ensure cohesion between the partial solutions.

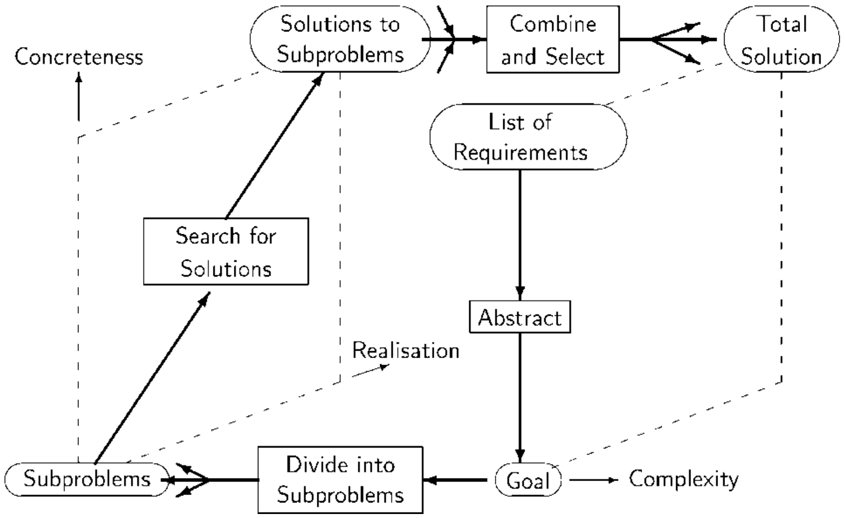

Figure 1. The space of the conceptual design phase (Krumhauer 1974). Ovals indicate information, rectangles show information processing.

In Kao and Archer (1997) it was noticed that domain experts design by reducing concreteness first, followed by reducing complexity (top–down breadth–first approach). This conforms to the model in figure 1. Also, the experts tended to work at a higher abstraction than non-experts. Non-experts did not use abstraction to its full extent. It was concluded that effective use of abstraction enhances design quality. Thus, support of abstraction may help the non-expert in moving toward the results of experts. However, another *possible* conclusion from this study is that experts perform better in designing than non-experts, whether they are provided with support tools or not.

These observations are compatible with the situation shown in Ottoson (1998). There it is mentioned that, in the 'drawing board environment', totality ruled over detail during design work. When the chief design engineer finished the systems design (as we would call it now), the senior designers focused on subsystems, and later on the designers worked out the details. This describes reduction of complexity in figure 1 and horizontal abstraction in Kao and Archer (1997).

For abstraction, models are well suited as they provide ways of presenting a relevant selection of the available information. It is therefore expected that they play an important role in the conceptual design phase. A model in this sense, can be defined as follows:

> **model** A schematic description of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics: a model of generative grammar; a model of an atom; an economic model. (From: *The American Heritage® Dictionary of the English Language*, fourth edition © 2000 by Houghton Mifflin Company. Published by Houghton Mifflin Company.)

It should be noted that a model is always a *limited* representation of reality; information that is not relevant to the purpose of the model is left out. Models created for investigating power consumption are therefore not suited for simulating dynamic behaviour.

In the next sections the use of models by conceptual designers is explored.

## 3. Literature on models in conceptual design

### 3.1 *Use of models*

When we look at different applications of conceptual design in the literature (Takasugi *et al.* 1996, Mekid and Bonis 1997, Mital *et al.* 1997, Zurro *et al.* 1997) we can find many models that are being used:

- Design criteria.
- Graphical model of the environment.
- List of requirements (quantified when possible).
- System budgets (for instance, used to divide the total electrical power over the subsystems, or to divide the total allowable positioning error over the subsystems).
- Morphological schemes.
- Kinematic diagrams.
- Sketches of possible solution(s).
- Physics models.
- Scenario for use of the device.
- Dynamic models based on simplified structure.
- Dynamic simulation results.
- Input/output data and data structures.
- Controller layout.
- Hardware/software framework.

- Detail design sketches of critical components.
- Finite element models and calculations.
- Numerical models and simulations.

Although some models seem to be more applicable in detail design, they can be, and have been, used in conceptual design. Finite element models, for instance, can be used in the conceptual phases to investigate feasibility without a completely defined geometry.

From the references it cannot be determined exactly what models are used in what part of the conceptual design phase, nor how the models relate to the properties concreteness, complexity and realization, or horizontal, vertical and general abstraction.

## 3.2 *Models in conceptual design support tools*

As the goal of this research is to create a support tool for conceptual and systems design, it is interesting to see what models are used in existing tools. Four tools are chosen:

- Schemebuilder (Bracewell and Sharpe 1996).
- 20Sim (van Amerongen and Breedveld 2003).
- Dymola (Dynamism 2005).
- CODSAS (Al-Salka *et al.* 1998).

**3.2.1 Schemebuilder.** Schemebuilder is one of the older conceptual design support tools. It was initially directed towards a largely automated design creation system. However, at present it is more aimed at creating a support tool that helps the designer, not replace him. Based on the work of French (1985) it uses the term '*scheme*' for a concept.

Schemebuilder uses bond graphs as its basis. However, other models that are used in Schemebuilder are (see figure 1 in Bracewell and Sharpe 1996):

- Yourdon diagrams.
- Three dimensional (3D) solid models.
- Function maps.

**3.2.2 20Sim.** 20Sim (pronounced Twenty Sim) was originally developed as a simulation tool. During the years it evolved into a much more versatile program. It provides the designer with a modelling and simulation environment that is also based on bond graphs and the corresponding constitutive equations. The user can see the models in different representations:

- Iconic diagrams.
- (Electrical) schematics.
- 3D models and animations.
- Block diagrams.
- Ideal physical elements.

This approach provides designers of different backgrounds with their own familiar model representations. In Vries (1994) is discussed how integrity between the different representations can be maintained.

**3.2.3 Dymola.** Dymola is quite comparable with 20Sim. However, it uses the language Modelica® as its basis. For different applications there are specific libraries with models and elements. The representations of the models to the user can be, just like in 20Sim, in several forms:

- Block diagrams.
- 3D models and animations.
- (Electrical) schematics.
- Iconic diagrams.
- Ideal physical elements.

**3.2.4 CODSAS.** CODSAS (the Conceptual Design Support and Analysis System) uses a 'new high-level programming language called design procedures programming language (DPPL)' (Al-Salka *et al.* 1998). This approach differs largely from the previous ones. The design process is programmed in a language that provides two data structures (document and integer). The document structure can be in one of six languages (in fact categories of models):

- Textual.
- Graphical.
- Structural.
- Hierarchical.
- Tabular.
- Morphological.

As the process is programmed, it is indicated which integers and documents (and of what type) are input and output. Not only the models are programmed (in one of the six languages) but also the tasks and activities.

## 4. Models used by conceptual designers

In order to investigate the use of models by conceptual designers further, several conceptual designer have been interviewed using a questionnaire. The questionnaire and the results will be dealt with in this section. The purpose was to make an *inventory* of models and relate their use to the space in figure 1.

### 4.1 *Questionnaire design*

Based on personal contacts, several persons have been identified that can be described as conceptual designers. They typically work in an environment where new designs have to be created (not mainly adaptive design), where advanced technology is applied and where people from several disciplines work together. Important is that they are involved in the early phases of a new design project.

The questionnaire is to be sent to these experienced conceptual designers by email or given in person. The responses can be sent to the author by email, fax or normal mail. To increase the number of responses, the questionnaire is designed to be filled out in approximately 15 min. The language is English, which is the second language for a large portion of the target audience. This is considered to be no problem, as the conceptual designers are typically highly educated and expected to be familiar with the English language.

First, a short introduction on the research project is given, including the position of the project in the research program of the Laboratory of Design, Production and Management at the University of Twente. Then practical information and the due date are given. Next, a few

Table 1. Scales used to rate complexity, concreteness and realization for the problems the interviewees are confronted with.

| | | | | | |
|---|---|---|---|---|---|
| Complexity: | Single device | – | Chain of devices | – | Structure of devices |
| | 1 | 2 | 3 | 4 | 5 |
| Concreteness: | Physical Principle | – | Working Principle | – | Construction element |
| | 1 | 2 | 3 | 4 | 5 |
| Realization: | Idea | – | Technical Drawings | – | Product |
| | 1 | 2 | 3 | 4 | 5 |

questions are asked about the conceptual designer such as age and design experience. Then, the working environment and the type of problems the designer is confronted with is asked. The designer is asked to rate the type of problems on a 1–5 scale for complexity, concreteness and realization. See the scales presented in table 1.

The larger part of the questionnaire is about the models used. To aid in listing the models, the following categories of models are provided:

(i) Textual models, divided into:
  (a) list-like,
  (b) descriptive, and
  (c) other textual models.
(ii) Graphical models, divided into:
  (a) abstract,
  (b) concrete, and
  (c) other graphical models.
(iii) Analytical models.
(iv) Other models.

For each of the models listed, the designer is asked to rate the complexity, concreteness and realization of the corresponding problems using the scales presented in table 1.

Finally, space is reserved for remarks from the interviewee on the questionnaire. Also it is asked whether the interviewee likes to receive more information about the outcome of the questionnaire and/or the research project.

The questionnaire can be obtained from the author.

### 4.2 *Expected results*

Conceptual designers typically work in the early stage of design, where values on the realization scale are low. On the other hand, conceptual designers should also be involved in the realization phase of a design project to safeguard the chosen concepts (Bonnema and Van Houten 2004). It is therefore expected that only a few models for problems with higher realization values will occur.

Also, as conceptual designers are often involved in complex projects, several models for highly complex problems are expected. As mentioned in Kao and Archer (1997) abstraction is a very powerful tool for conceptual design. As both the concrete and abstracted problem have to be considered, both high and low values are expected on the concreteness scale.

### 4.3 *Results*

The results of the questionnaire are summarized in table 2. The response rate was little over 50%. The conceptual designers interviewed are relatively young and have approximately 12

Table 2. Summary of results of the questionnaire.

| | |
|---|---|
| Surveys | |
| Sent | 13 |
| Returned | 7 |
| Response | 54 % |
| Respondents | |
| Average age | 37 |
| Average design experience | 12 years |
| Experience of which conceptual design | 10 years |
| Problems | |
| Complexity | 3.5 |
| Concreteness | 3.4 |
| Realization | 2.2 |
| Models | |
| Total number | 86 |
| Different | 45 |

years of design experience, most of which in the field of conceptual design. This may lead to the conclusion that conceptual design is a natural way of thinking for some people who will use it from early in their design career. The problems the designers are confronted with are above average in complexity and concreteness, but below average in realization. Several designers mentioned a large range on these three ratings. As can be seen in table 2, a total of 86 models have been identified, of which there are 45 different ones. It should be noted that minute differences in the descriptions as given by the interviewees have been removed.

One of the respondents gave vague answers to the models he used (only the type or the discipline involved is mentioned). Therefore his answers are left out of the following, more detailed, analysis. This means that there were 78 models, of which 43 different ones will be analysed (again with minute differences removed). In section 5 the models mentioned by this respondent will be taken into consideration.

The number of respondents (seven) is too small to perform statistical analysis. As the purpose was to create an inventory of models, statistics are not needed.

A more detailed analysis of the results is presented in figure 2. Here six plots are shown, each representing one realization value shown above each plot. Within each plot the number of models for each combination of complexity and concreteness is shown. A few models were given no complexity, concreteness and/or realization rating; these are shown as 0 in figure 2. In addition to that, table 3 shows for each complexity, concreteness and realization value how many models are mentioned in each of the categories. The models mentioned are distributed over all categories.

It is clear that only a few models for problems with realization $\geq 4$ have been identified. This was expected. The models used for problems with a larger realization value were among a few others: assembly procedure, component testing, interface descriptions, and prototype testing. These types of models typically occur in the integration phase of a project where the fit between separate modules, both in geometry and functionality, has to be checked. The conceptual designer will be involved because of his overview over the entire system (as in Bonnema and Van Houten 2004). These models have more to do with *verification* and *integration* than with design.

For realization $= 1$, most models identified are relevant for higher complexity and lower concreteness. The largest number of models correspond to problems with realization $= 2$. In particular, for problems with concreteness $= 2$ and complexity $= 2$ and 3, many models have been listed. Looking at table 3, it can be concluded that in particular textual descriptive models are used intensively. Also, textual list and graphical concrete and abstract models are used, be it less frequently.

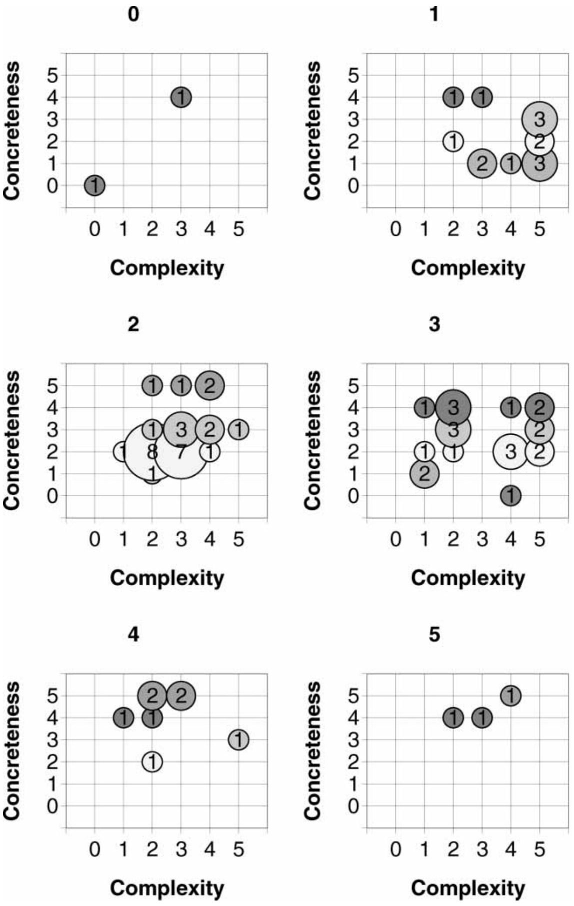

Figure 2. Results of the questionnaire. Each plot represents one realization value (shown above the plot). The horizontal axes represent complexity and the vertical axes concreteness. The number of models are indicated by the area of the bubble and the number in the centre of the bubble.

Table 3. Results of the questionnaire showing the number of models in each category as function of complexity, concreteness and realization.

| | | Complexity | | | | | | Concreteness | | | | | | Realization | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of models | Total | – | 1 | 2 | 3 | 4 | 5 | – | 1 | 2 | 3 | 4 | 5 | – | 1 | 2 | 3 | 4 | 5 |
| Textual list | 12 | | **2** | 2 | 1 | **5** | 2 | 1 | **2** | 3 | 2 | 2 | 2 | | 3 | 5 | 3 | 1 | |
| Textual descriptive | 14 | 1 | **2** | 4 | **4** | 1 | 2 | 1 | **2** | **6** | 3 | 2 | | 1 | | **8** | 3 | 1 | 1 |
| Textual other | 3 | | | 3 | | | | | | 2 | | | 1 | | | 2 | | 1 | |
| Graphical abstract | 14 | | | 3 | 2 | 2 | **7** | | **2** | 5 | **6** | 1 | | | **5** | 4 | 4 | 1 | |
| Graphical concrete | 17 | | 1 | **6** | **4** | 3 | 3 | | **2** | 5 | 3 | **5** | 2 | | 3 | 4 | **8** | **2** | |
| Graphical other | 3 | | | 2 | 1 | | | | | 1 | 1 | 1 | | | | 1 | 1 | | 1 |
| Analytical | 8 | | 1 | 2 | **4** | | 1 | | 1 | 4 | 1 | 2 | | | 3 | 3 | 2 | | |
| Other | 7 | | | 3 | 2 | 1 | 1 | | | 2 | | 1 | **4** | 1 | | 2 | 1 | **2** | 1 |
| Total | **78** | 1 | 6 | 25 | 18 | 12 | 16 | 2 | 9 | 28 | 16 | 14 | 9 | 2 | 14 | 29 | 22 | 8 | 3 |

*Note*: The highest number (>1) in each column is shown in **bold**.

Table 4. The models mentioned more than once, together with their frequency ($f$) and category.

| | | | Average | | |
|---|---|---|---|---|---|
| Model | $f$ | Category | Comp | Conc | Real |
| Budget | 2 | Textual list | 5.0 | 2.5 | 1.0 |
| Analysis of physical behaviour | 2 | Analytical | 3.0 | 1.5 | 1.5 |
| Mathematical model | 6 | Analytical | 2.7 | 2.2 | 1.7 |
| Block diagram | 3 | Graphical abstract | 4.0 | 2.7 | 1.7 |
| Sketch | 6 | Graphical concrete | 3.2 | 2.7 | 2.0 |
| Scenario | 2 | Textual descriptive | 4.0 | 2.5 | 2.0 |
| Functional diagram | 3 | Graphical abstract | 3.3 | 3.0 | 2.3 |
| Specification | 4 | Textual list | 3.3 | 3.5 | 2.5 |
| Description | 2 | Textual descriptive | 2.5 | 1.5 | 2.5 |
| Scheme | 3 | Graphical abstract | 3.0 | 1.7 | 2.7 |
| Drawing | 2 | Graphical concrete | 3.0 | 3.0 | 3.0 |
| Computer-aided design | 7 | Graphical concrete | 3.0 | 3.6 | 3.4 |

*Note*: The models are shown in order of increasing average realisation of the corresponding problems (Real). Also shown are the average values for complexity (Comp) and concreteness (Conc).

For realization = 3 there is a larger variation for both complexity and concreteness. The total number of models identified for this realization value is a little lower than for realization = 2. By far the largest number of models are in the graphical concrete category. As already mentioned, the number of models for problems with large realization values is small.

Table 4 presents the most often mentioned models plus their frequency and average complexity, concreteness and realization values of the corresponding problems. (Systematic or methodical design and value engineering have been mentioned several times as well. However, these are design methods, not models. They are therefore left out of table 4.)

The order chosen in table 4 is increasing realization. Referring to figure 1, it can be said that during a design, project complexity and concreteness may increase and reduce; realization, however, only increases (albeit not continuously). Thus, ordering the models mentioned by increasing realization values gives an indication for a logical sequence of models.

The model with the lowest realization value (and thus applicable in the earliest phase of a design process) is a budget. The reported frequency in table 4 is 2, but the interviewee whose response has been left out of the analysis, reported intensive use of budgets throughout the design process. Interesting to note is also the high score of complexity for budgets.

Three models with comparable realization values are analysis of physical behaviour, mathematical model and block diagram. Of these, block diagram has the highest complexity value. Analysing physical behaviour is on one hand creating a proper (ideal) physical model of the situation, and on the other hand analysing it with mathematics. These two models are therefore closely related. Note the higher value for concreteness for the mathematical model. To perform mathematics, more concrete knowledge is needed (parameters, etc.).

Next on the realization scale are sketch and scenario. Sketch is the first graphical *concrete* model on the realization scale. A scenario describes the use and context of the product to be designed.

The next group of models contain two graphical abstract models (functional diagram and scheme), and two textual models (specification and description). A scheme can be nearly any graphical abstract model, such as functional and block diagrams, electrical schematics or timing diagrams.

Finally two graphical concrete models are mentioned: drawing and computer-aided design (CAD). These two are closely related. However, a drawing can be made by hand. It can be a worked out sketch that is used to detail the product using CAD. Its lower realization and concreteness values are therefore logical.

It can be concluded that all models that are mentioned more than once are important for a proper conceptual design process. In the next section the results will be interpreted and discussed further.

## 5. Discussion

This section will discuss the results of the questionnaire into more detail providing the basis for the interviews in the next section and for the conclusions in section 7. Although the response rate is fairly high, the actual number of responses is only seven. Thus, the results have to be considered with caution. In particular it should be noted that powerful statistics are not applicable with this small number of results. On the other hand, as the purpose of this questionnaire was to create an inventory, the number of models mentioned is large enough.

All categories of models are used intensively. Graphical, textual and analytical models are used by conceptual designers throughout the process. At lower complexity problems, both textual and graphical models are used. For high complexity, the graphical abstract and textual list models prevail. Problems with a low concreteness can be handled using models in all categories. As concreteness increases, the graphical models are used more often. For higher realization values, the graphical concrete models play the major role. At lower realization values, textual descriptive and graphical abstract models are used more often.

As noted earlier, conceptual designers are mostly involved in the early part of the design process, where realization values are low. However, they produce plans for entire solutions, thus both complexity and concreteness will be large at the end of the conceptual phase. Some conceptual designers will be involved in the integration and testing of the final product. They will use models for problems with high realization values.

Let us look at the results of the questionnaire in tables 3 and 4 and figure 2 and compare it with the model in figure 1. The path in the model by Krumhauer is to start from high complexity and concreteness, but low realization; first reduce concreteness, followed by a reduction in complexity. By solving the individual subproblems, the concreteness and realization are increased. Then these individual solutions are combined, thus increasing complexity.

As realization increases throughout the conceptual design process, we can look at whether the models mentioned follow the pattern of first reduction in concreteness and complexity, then increase in concreteness and then in complexity.

Figure 2 shows that realization $= 1$ corresponds mainly to models with high complexity and low concreteness. No models are mentioned for both high complexity and high concreteness values. For increasing values of realization, the values for concreteness and complexity vary more. Krumhauer expects high complexity and concreteness values for high realization values. The results of the questionnaire do show models with high concreteness and models with high complexity. However, the number of models for problems with high complexity and high concreteness and high realization is very low.

It appears that the model by Krumhauer (1974) is not fully supported by the results of the questionnaire. Problems are represented in the early part of the design process by models that are less concrete than Krumhauer suggests. This can partly be caused by the fact that the initial abstraction is performed without models, or that the designers interviewed have a perception of lower concreteness in the early stage of the design. For the higher realization values, where Krumhauer expects high complexity and high concreteness, the results of the questionnaire are neither supportive nor negative.

Looking at Kao and Archer (1997), where it is concluded that experts use (vertical) abstraction intensively, we can conclude that indeed the experts interviewed approach a problem at an abstract level. Table 3 presents many models for lower concreteness values. Also, the interviewees use horizontal abstraction: the lower complexity values also have many models.

Next let us look at the frequency of models mentioned, and the average complexity, concreteness and realization values (table 4). Again as realization is low in the beginning of the design process and increases during the work of the conceptual designers, a logical sequence of models in the design process is as follows:

(i) System budgets for the total view, to handle high complexity and to provide a means for splitting the top level requirements into requirements for the subsystems.
(ii) Mathematical models for allocating the budgets to (critical) elements. At first rough calculations, moving to more detailed and precise mathematical models. These can also be used for budget verification later on in the design process.
(iii) Analyses of physical behaviour in combination with mathematical models.
(iv) Block and functional diagrams (possibly several other schemes) to model the functional dependencies in the design and to maintain overview over the entire system under design.
(v) Specifications to record the decisions on the top level design and functional characteristics. Also interface specifications are needed.
(vi) Sketches to develop possible embodiment details.
(vii) CAD as a tool to implement and monitor the embodiment and detail design and to create (technical) drawings.

Additionally, sketches will be used to complement and illustrate the other models mentioned earlier. Also, there should be space to create and maintain descriptive models like scenarios.

The vague answers of one respondent that were left out are not in conflict with this sequence. In fact they support the use of budgets to cope with complexity. Also, the interviews mentioned in section 6 support this list.

Interestingly, the models mentioned do not correspond to the models used in the conceptual design tools of section 3.2. In particular, budgets, specifications, scenarios, and sketches are not available in the four tools. CODSAS may be able to represent budgets as a tabular document. In the description by Al-Salka *et al.* (1998), however, they are not mentioned. The mathematical models, physical models, block diagrams, and CAD are available in most of the four tools.

The list is not intended as a rigid structure in which the models should be used. Instead, it provides a framework for a support system for conceptual design. Such a system has to incorporate means to handle these models. Equally important is the fact that a system can handle the connections and transformations between these models.

It is worthwhile to mention the research in Vries (1994). Here three types of models are used in a closely interlinked manner: iconic diagrams, bond graphs and the THESIS modelling language. All three of these models are used for problems low on the realization and concreteness scales. Complexity of the models may be high, but it remains to be seen whether complex bond graphs and THESIS models can be sufficiently easily handled by the designer. Budgets and functional block diagrams at several levels of complexity and/or concreteness may help in handling complexity. Combined with the principles in Vries (1994), connecting the models mentioned above may be feasible.

## 6. Interviews

The results have been discussed with three of the conceptual designers in order to verify the results. In these discussions the kind of design issues the conceptual designers face have been discussed, together with their approach. Next, the model by Krumhauer (figure 1) was treated, including the models used in the different steps (abstract, divide into subproblems, search for solutions and combine and select). Finally, the list of models for the conceptual phase (section 5) was discussed.

The design problems described varied considerably, but in all cases a complex context and a complex, multi-disciplinary solution were mentioned. The approach consisted in all cases of a structured method, based on, or equal to systematic design (Pahl and Beitz 1996). One interviewee also mentioned the use of TRIZ (Altshuller 1997, 1999) as an approach to the problems he faced.

On the model by Krumhauer, there were several interesting remarks. In general the route though the design space was recognized. However, iteration is not shown in the model, but is present in reality. Also, in case of extreme specifications, it is important to investigate the feasibility in an early stage of the design process. This cannot be derived from the model by Krumhauer. Also, as mentioned in section 5, the first abstraction step in the model was less recognized. One interviewee mentioned that in his opinion the goal is often present *before* the requirements are defined. The models used in the four steps of the model by Krumhauer were a subset of the ones mentioned in the responses to the questionnaire.

The main result of this research is the list of models presented earlier. As stated, this list has been discussed in the interviews. The question was whether the models were recognized in approximately this sequence. One of the interviewees did not recognise the use of system budgets for errors, performance, power use, and soon. However, the use of a space budget in a product with a strict size constraint was used. One interviewee mentioned the fact that a budget can only be made when a functional model is already created. This asks for an integrated approach to these two models. Two of the interviewees did not need CAD in the conceptual phase. It was considered as a tool for detailing the product. One interviewee even considered the use of CAD highly overrated.

All the models in the list in section 5 were considered important. Additional models that may be required were patents, comparisons with other products, and an integrated system for combining mechanics and electronics.

## 7. Conclusions

As conceptual design is the phase in which different fields of science and practical knowledge have to be handled in order to define the basic operation and structure of a new product, a large amount of information has to be handled. To accomplish this, models are used by the designers. Each model is able to represent and manipulate a specific combination of information. To investigate the use of models by conceptual designers a small-scale literature study was made. Different models are listed, without the possibility to link them to the model presented in Krumhauer (1974).

A questionnaire has been designed that is used to make an inventory of the models used by conceptual designers. Also the complexity, concreteness and realization of the problems for which the models are used are asked. This enables linking the models to the model by Krumhauer (1974). The questionnaire was sent to experienced conceptual designers; the response was 54%.

The questionnaire shows that the designers interviewed have started doing conceptual design shortly after having started designing.

The results of the questionnaire also show that conceptual designers use many different models throughout the design process. Each combination of complexity, concreteness and realization asks for a specific type of model. A possible sequence of models has been identified that can be used in a support system for conceptual design. However, there is no information yet on the connections between the models in this sequence. It is worthwhile to investigate further as a system that uses these connections can help in investigating the consequences of design decisions early in the process. Also, such a system may help in guiding the design process.

The models provide a means for handling the information at different stages of the conceptual phase. They can be used for communicating and analysing problems. For solving the problems, other techniques and methods are required. One can think of traditional methods such as brainstorming/brainwriting and morphological schemes (Pahl and Beitz 1996). A very powerful method is TRIZ, which helps to formulate the problem, but also provides tools (40 principles, contradiction matrix, evolution of technical systems, S-field analysis) that guide the designer to several solutions.

The model by Krumhauer is not supported by the results of the questionnaire, but in the interviews the conceptual designers recognized the route through the design space. The reduction in concreteness at the beginning of the conceptual phase is not recognized in the models listed by the designers. In the interviews this step was the least recognized. The increase in complexity at the end of the conceptual phase cannot be found in the results either. However, this does not mean the model by Krumhauer is incorrect. Possibly the reduction in concreteness is performed by the designers without the use of models. The same may hold for the increase in complexity.

As complexity is a characteristic of the problems conceptual designers are confronted with, it is paramount that models are used that can handle these highly complex issues in the earliest stages of the conceptual phase. The models for these issues that are listed in the questionnaire are budgets, block and functional diagrams, and specifications. These should therefore be included in our conceptual design support system. As a backbone, a mathematical approach should be considered. Representation of the systems using iconic diagrams or ideal physical elements would be convenient as well.

This article has only looked at the most frequently mentioned models. However, it is expected that by using the models in section 5 most critical issues in conceptual design can be handled.

## 8. Future work

An important issue that needs attention are the relations between the models mentioned at the end of section 5. By investigating these relations, an architecture may be defined for a support system. In particular, maintaining integrity between models on one level and methods for propagating changes in models on one level to levels further up and down the list in combination with collaborative work appears to be a challenge.

Also, how functional models coupled to system budgets can aid in conceptual design will be investigated further.[†]

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[†] This article includes words that are or asserted to be proprietary terms or trade marks. Their inclusion does not imply they have acquired for legal purposes a non-proprietary or general significance, nor is any other judgement implied concerning their legal status.

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