Problem solving in design: a comparison of three theories
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Published: 01/01/1990

Document Version
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Problem solving in design: 
A comparison of three theories

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OCTO-report 90/03
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Abstract

Recently design processes received considerable attention from the side of cognitive psychologists. Cognitive psychologists study the design task as another example of a problem solving process. In this paper, three models of the design process are discussed. These models come from both architects and psychologists. Two aspects are considered important: the ill structured nature of the design task, and the large body of design (domain) knowledge that is involved in accomplishing the design task. Finally, some preliminary remarks are made about information presentation to architects.

1 Introduction

This paper presents the first overview of literature within the GRIOTTO project. The GRIOTTO project aims at studying graphical representation as a means of transferring knowledge to technical designers. There is a growing body of design knowledge from different disciplines, for example from environmental psychology. Research knowledge does not always reach the designer. New findings however should be accessible for designers. The project studies information presentation to designers in architecture. The first step is to study design processes themselves, in order to be able to answer questions regarding information presentation.

The present paper aims to give an overview of the various models of the design process. Most of the theories, both architectural and psychological, use concepts developed by Newell and Simon (1972) to study design as a problem solving process. Therefore, the main ideas of this paradigm will be presented, and the characteristic features of the design process are mentioned. In part three, three models of design as a problem solving process are presented, these theories are compared and some general conclusions are given. The final section deals with the role of knowledge and information in design, information retrieval from external sources and the presentation of design information.

This research is carried out within the OCTO program 'Transfer of technical knowledge and skills'.

2 Design and problem solving

2.1 Design: definitions

This paper is about design processes. A designer is said to be someone producing a plan for what is to be made. If designing is to instruct making, it must produce something that represents what is to be made. Therefore the designer's world is one of representations (Habraken, 1988).

In inspecting the literature it turns out to be very difficult to catch the essence of design in a definition. Different definitions of design stress different aspects, but there are common aspects. Two descriptions are cited here. The English Language Dictionary (1987) states that when you design something

'you plan and create a picture of it in your mind and you make a detailed drawing of it from which it can be built or made'.

3
A definition from Boekholt (1984) describes design as

'the activity that aims at representing an innovative solution to a particular problem, a solution which did not exist before in the mental world of the designer' (p. 27, translated from Dutch).

These descriptions present two important aspects of design that appear to be central to most definitions. Design deals with representations, from images in the mind of the designer to paper drawings, and design aims at finding a solution to a particular problem. Hence, design is seen as another domain of interest in applying and testing theories of information processing and problem solving.

Design processes have received considerable attention in the field of architecture as well as in cognitive psychology. Theories of design developed in architecture are based on the observations of experienced architects and teachers in architecture. These theories are developed in order to clarify the nature of the process for design practice and education, and to provide a methodology of design. Researchers in cognition, however, are more interested in the psychological components of design as a problem solving process.

Hamel (1989) argued that models of the design process presented by designers and teachers in design are often prescriptive in that they prescribe the way in which a design ought to be arrived at, rather than the process as it takes place in reality. Models developed from a cognitive psychological perspective aim at a description of the process. A characteristic of descriptive psychological models is that they should be empirically tested (Hamel, 1989). Although architectural and psychological models represent a different approach to the same process, there should be a correspondence between the subjective, ideological view of designers and the objective general view of scientists (Thomas and Carroll, 1979). These authors argue that in order to understand design one also has to experience what designing is like, a view shared by architects. We probably need both the experience of designers as well as tools and insight of researchers in cognition.

In the next section main concepts of human problem solving theory will shortly be described. The design process can then be situated within this theory. In addition, the design task can be compared to other tasks that have been studied within this problem solving paradigm.

2.2 Human Problem Solving: concepts

Newell and Simon (1972) set out to study human task performance. They started by studying moderately difficult problems of symbolic nature, such as cryptarithmetic, logic and chess. Although restricted to certain tasks, their theory should provide a tool to study all sorts of symbolic behaviour.

The theory assumes that people exhibit goal directed behaviour, that is that they are motivated towards a goal, so that adaptive, rational behaviour is demanded by the situation or environment. A person is confronted with a problem when he wants something and does not know immediately what series of actions he can perform to get it. In order to reach the goal, information has to be processed. Humans are seen as processors of information. The characteristics of such an information processing system are the existence of a set of elements (symbols), relations between these elements (symbol structures), a memory capable of storing and retaining symbol structures and a processor that consists of information processes that act upon symbol structures.

An information processing system performs operations on representations. Although operations or processes received more attention from researchers, an adequate representation of the problem at hand is of crucial importance for finding a solution to the problem. Newell and Simon give the nine
dot problem as an illustration of the importance of an appropriate representation. In 'the nine dot problem' people have to draw four lines through nine dots arranged in three rows of three dots without lifting their pen. In this problem a solution is quickly found only when people come up with the idea of having lines that extend outside the square formed by the dots (Newell and Simon, 1972).

Problem solving takes place by search in a so called problem space. This problem space is taken to be the fundamental organization for all goal-oriented symbolic activity ('problem space hypothesis', Laird et al., 1987). The problem space consists of 1) representations, 2) the information processes, 3) some representation of the initial state and the desired final state or goal and 4) the total knowledge available. A subgoal is set up whenever the immediate knowledge is insufficient to make a decision, for instance when a decision is needed with regard to the selection of a process or operator. In fact, a subgoal is created for any problematic decision ('universal subgoaling', Laird et al., 1987). Problem solving can be effective only if significant information is encoded in the problem space, where it can be used by the problem solver. The information that is available in the problem space is in part determined by the task environment, but there can be no guarantee that all the relevant information in the task environment is reflected in the problem space.

Newell and Simon used verbal behaviour to get enough data about each individual subject to identify what information he has and how he is processing it. Later on a computer model was developed in trying to provide an architecture of general intelligence capable of performing the full range of cognitive tasks (Laird et al., 1987).

2.3 Design as a problem solving process

Architects themselves already referred to design problems and design solutions (Lawson, 1980) or to design as a basic problem-solving process (Wade, 1977). Hamel observed that aspects mentioned in definitions of design are compatible with concepts of a theory of human problem solving (Hamel, 1990). Both Akin (1986) and Hamel (1990) argued that design can also be seen as problem solving on psychological grounds. First, design is a goal-directed activity, it is a form of problem solving where individual decisions are made towards the fulfilment of objectives (Akin, 1986). Secondly, at the outset of the design process the available design knowledge is not sufficient to produce a design immediately, and third the ultimate design proposal will be tested for its qualities (Hamel, 1990).

In studying design within the problem solving paradigm, Akin (1986) assumes that, although designers' knowledge and behaviours may vary, their basic information-handling activities such as encoding, manipulation, and recall of information are essentially similar to the activities observed in other task contexts.

2.4 Characteristics of design problem solving

The symbolic tasks that were studied by Newell and Simon were relatively easy to describe. However, the theory should also offer the possibility to study other more real-life tasks. Real-life tasks differ with respect to a number of aspects from the originally studied tasks. Two distinctions are important for the study of the design task. First, the distinction between ill structured and well structured problems (Simon, 1973). Second, the distinction between tasks that involve little or no domain knowledge and tasks that involve large amounts of knowledge. These tasks involving substantial domain knowledge are called semantically rich (Bhaskar and Simon, 1977). These two extensions and their relation to the design task are discussed below.
Ill structured problems

The kind of simple symbolic problems that were studied initially, are classified as well structured problems. A problem is called more or less well structured to the extent that their exists a problem space in which can be represented 1) all possible states (initial state, intermediate states, goal state) 2) possible and legal transitions between states (operators) and 3) knowledge about the problem and the external world. In addition for a problem to be well structured there should be a criterion for testing any proposed solution. An ill-structured problem lacks the typical characteristics of a well structured problem.

Simon (1973) argues that the boundary between well structured and ill structured problems is vague and fluid. According to Simon the problems that are studied in general, like cryptarithmetic, are ill structured, but became well structured only because they were prepared for the problem solvers. No well structured problems exist, only ill structured ones that have been formalized. In real world much problem solving effort is directed towards structuring problems and only a fraction of it at solving problems once they are structured. However, Simon argues that real ill structured problems should not be left unstudied. He claims that the methods applied to relatively well structured problems should be used to study ill structured problems as well. In this way, ill structured problems will not be put aside as tasks too complex to study (Simon, 1973). He takes designing as an example, being very different from standard puzzles. Design has been placed towards the ill structured end of the continuum, because there is no finite problem space in which can be represented all possible states or design solutions, transitions are not easily represented and not all knowledge about the problem and the external world will be represented. In addition, criteria to test a design are often unclear, especially when one considers aesthetics (Simon, 1973). Furthermore, it is difficult to decide the limits to relevant information, there is no easy method to generate all alternative solutions at every step and it is difficult to decide whether or not the goal has been reached (Boekholt, 1984).

According to Simon, designing can take place by sequentially dealing with subproblems or subgoals in the process. The ill structured problem should be decomposed into a number of smaller well structured problems. The relevant information regarding one subproblem can be held in memory. The design process as such is a combination of a general problem solver, which at any given moment finds itself working on some well structured subproblem, with a retrieval system, which continually modifies the problem space by evoking from long-term memory new constraints, new subgoals, and new generators for design alternatives. This conception of the design process resolves the difficulty of having to bring into a memory all the relevant information about the design problem at once (Simon, 1973). However, dealing with well structured subproblems one at a time introduces the need for some sort of control function that monitors the process. Simon imagines designing as a task that evokes from memory a list of topics to be considered, and some overall organization or executive program. Some of the models of the design task that will be discussed in the next chapter, do indeed provide for such a control function. In addition, the solutions to the subproblems have to be interrelated to produce an overall design solution, and this overall solution still has to be judged against criteria which are not always very clear, for example aesthetic criteria. The entire design problem therefore remains ill structured, although it can be divided in manageable well structured parts.

Semantically rich domains

Another distinction that is made concerns problems that demand specific domain knowledge. Most of the tasks studied initially, like cryptarithmetic, did not require large amounts of domain knowledge. In fact, general problem solving processes are sufficient to solve these problems, and all the knowledge is included in the problem statement. However, real-life tasks often involve knowledge
which is not included in the problem statement. How should these tasks be studied?

Bhaskar and Simon (1977) carried out a study in engineering thermodynamics. Engineering dynamics is considered a task that demands from the subject large amounts of prior semantic knowledge. One could argue that problems in such a domain are solved merely by using common problem solving processes that then draw upon specific knowledge of that domain. This knowledge is to be found for instance in a textbook on the subject. However, Bhaskar and Simon found that apart from knowing what information has to be used, it is also important to know how the information has to be organized and used to solve the problem. In other words, one has to know how to handle the information, specific procedures are needed to handle the information in the domain. Bhaskar and Simon conclude that the problem solving that takes place in semantically rich domains resembles closely that which has been observed in task environments having less rich semantic content. The semantic information takes the form of data structures in long term memory and of procedures. Important is the ability to recognize the situations in which the knowledge has to be retrieved at appropriate times during the process (Bhaskar and Simon, 1977). This knowledge about problem situations or situational knowledge (DeJong, 1986) will be discussed in the final section of this paper.

The design task is considered a task in a semantically rich domain because of the enormous amount of design knowledge about buildings, construction etc.

3 Theories of the design process

In this section three theories of design will be presented. The theories differ in background and they stress different aspects of the design task.

The first theory I want to present comes from the architectural discipline. Boekholt's model is an example of an architectural model which incorporates insights from psychology. It is more refined than architectural models in general. It stresses the development of a large problem space containing many different possible solutions to the design problem. Because the model explicitly stresses the importance of different solutions for good design it can be seen as a rather prescriptive theory.

Another model developed by an architect is that of Akin. Akin's model is a psychological model and empirically tested to a certain extent. Akin stresses the information processes that take place during design. These information processes are described in such a way that they can also be implemented on a computer.

Finally, a model coming from a psychologist is presented. Hamel's model not only incorporates problem solving concepts but other psychological constructs like schema's as well. Hamel describes the activities that are carried out by an architect performing a design task. This level of analysis represents a macro level whereas Akin's model takes place on a more micro level. Hamel empirically tested his model using protocol analysis of the thinking-aloud protocols of architects designing.

The kind of questions which will be asked about the theories of the design process are: How are design problems, solutions and knowledge represented? What are the processes that operate on these representations? How is dealt with the large knowledge base and the aspects of ill structuredness?

3.1 Boekholt (1984): The structure of architectural design processes

Boekholt (1984) presents a detailed description of the architectural design process. It is an example of a model developed from experience and observations in the field of architecture. The
model incorporates concepts from human information processing and problem solving.

Representations

According to Boekholt, design starts with a vague description or image and develops gradually to a more accurate description or image. From the definition of design problems as essentially large, complex and ill structured and the limited processing capacity of human memory follows the need and importance of sectioning the problem into a number of related well structured subproblems. Boekholt identifies levels and aspects to provide a way of sectioning the problem.

A design problem can be studied at different levels. An architect has to consider the furniture in a room, the arrangement of rooms and corridors in a building, the grouping of buildings in a street etc. Hence, an architect studies how to arrange certain elements in a particular situation. A situation with its elements is called a level, and several different arrangements of elements in a situation are called variants. Furthermore, a situation (e.g. a house) at one level is an element at a higher level (e.g. street level) and vice versa. Boekholt argues that the identification of levels is the first step in decomposing the ill structured design problem into well structured subproblems. Studying a subproblem on a level reduces the number of elements which have to be activated in memory at a time. In addition, the hierarchical structure in levels must preserve the relation between the levels.

Alternatively, the design problem can be sectioned according to different functions the object has to fulfil. Different functions impose different constraints. Boekholt identifies three aspects which are of importance to the designed product. These aspects have to do with the fact that the designed object has to be built, used and maintained. These three aspects impose different constraints and thus different design solutions are developed when concentrating on one particular aspect. These design solutions also are called variants.

The problem space in Boekholt's model consists of variant design solutions. These variants are combinations of level and aspect solutions. This problem space is in principle endless, but constrained by both the problem definition and the personal characteristics of the designer (Boekholt, 1984).

Processes

Boekholt describes the elementary operations cycle as a building block in design processes. This cycle consists of four operations:

Formulation of the problem: the actual state, the goal state and the difference between these two states is established.

Formulation of starting points: the situation and elements are identified and spatial-physical starting points are identified.

Generation of variants: many essentially different variants are generated.

Evaluation of variants: the variant solutions have to be compared and judged against criteria.

The outcome of the last operation (evaluation) can influence the starting points which were formulated at the outset, or reveal new facts and criteria about the problem.

Within a cycle, information is combined to form new information structures or images. According to Boekholt the design process can be characterised by four phases in which a number of operations cycles take place. In each phase the emphasis will be on one of the four operations. The sequence of stages thus operates on the ultimate goal of producing a design, as well as on subgoals, in producing level and aspect solutions.
Conclusions

Structuring the design problem into level and aspect systems provides a way of subdividing the large ill-structured problem into multiple component problems which are well structured. In studying one subproblem at a time, not all knowledge pertaining to the design problem has to be considered at the same time. However, Boekholt’s model does not specify explicitly a control function or procedures regulating the solving of subproblems. But, he does claim that the decomposition in level and aspect subproblems is learned through experience, and a characteristic of the expert architect.

The problem space consisting of variants differs from the problem space of simpler tasks. The variants each have to be seen as possible solutions in their own right, whereas in simple tasks, impossible or ‘wrong’ solutions are quickly abandoned, in favour of the search for an ideal solution. As a consequence, evaluation of variant solutions is necessary to determine the optimal solution. In the evaluation phase, different solutions are compared on several criteria which were specified at the outset of the process. In addition, during evaluation new criteria can be discovered.

A design process consisting of phases and cycles, containing the same sequence of operations can be compared to the notion of universal subgoaling, where the same problem solving process is observed to solve the supergoal of performing the task, as well as in reaching every subgoal that is evoked.

Many students in architecture and even professional designers often direct themselves in the first stages of the design process towards an ideal solution. Nevertheless, Boekholt started from the conviction that the essence of good design is the generation of variant solutions. This illustrates the prescriptive nature of his model. Boekholt’s description of the design process relies strongly on his personal observations, no empirical studies have been conducted, but the model proved to be very useful in structuring design education.

3.2 Akin (1986): The psychology of architectural design

Akin (1986) viewed the developments in the area of human problem solving as an opportunity for understanding the cognitive basis of architectural design. He aimed at a descriptive model of design as a foundation for design research, education and practice. The assumptions of a theory of information processing are taken as a point of departure in the study of design. Akin defines the counterparts of the components of the theory for design, a model appears with appropriate representations and processes for design.

Representations

Akin discusses three representational paradigms on their merits for representation of information in architecture. These are production systems, conceptual inference structures and chunks.

Production systems:

A production consists of a condition and an action part, when the condition is met the action must be taken. A production system contains lists of productions and sets of rules regulating control. According to Akin, production systems are an ideal device for modelling the goal-directed behaviour of designers.

Conceptual inference structures:

Conceptual inferences do not necessarily obey logical rules of inference, but are considered valid in everyday tasks. Akin argues that their ability to accommodate contradictory and imprecise relationships make conceptual inferences appropriate for use with ill-structured and informal problems.
Chunks:
Finally, Akin argues that in task domains with predominantly spatial problem spaces, like chess for example, chunks are the most robust information structures which have been shown to account for memory functions. Akin argues that hierarchical clustering of information, critical in spatial representations is a suitable memory organization for design knowledge.

Although there are inconsistencies, Akin proposes to use all three models of memory, as a description of functionalities present in humans.

Processes
Akin stresses the processes that operate on information, and distinguishes information acquisition, information representation, information projection, information confirmation and regulation of control. These processes are then described with the help of flow diagrams with TOTE units as essential building blocks. A TOTE unit (test - operate - test - exit) is a simple control mechanism that characterizes simple behaviours.

Information acquisition: Information is looked up by this process through visual search e.g. inspection of texts, maps, and sketches, verbal inquiry and search of memory contents.
Representation of information: Information has to be represented in written text or spoken word, through graphics and in memory.

These two processes ideally produce a good representation of the design problem, that is a problem space optimal for problem solving. Akin claims that the mode of representation that corresponds to these processes is mainly the chunk mode of memory organization.

Projection of information: This process permits to infer new information and relations from acquired knowledge.
Confirmation of information: The new implications produced by the projection process then have to be tested for consistency by the confirmation process.

According to Akin, the conceptual inference structures underlie these latter two information processes.

Regulation of control: Subsequently, a process is necessary to reduce the size of the problem space or search space. This process Akin calls regulation of control and concerns mainly heuristics to focus attention on a part of the space which supposedly contains the solution.

Production systems are supposed to be the basis for regulating this transmission of control.

Akin incorporates the processes in a flow diagram, he identified legal (12) and illegal transitions (8) between processes. In four analyzed protocols Akin found 85% of the transitions falling in the predicted categories. He concluded that in spite of some deviation from the predicted norm (100%, chance norm = 60%), the observed frequencies were probabilistically consistent with the apriori model.
In addition to the primitive processes, Akin identified process sequences that correspond to the search methods described by Newell (cited by Akin, 1986). The methods are generate-and-test, pattern matching, hill-climbing, heuristic search, and induction. The generate-and-test sequence turned out to be the most prevalent (56%) in the analyzed protocols. In architecture this method consists of projection of information (generate a partial solution), confirmation of information (test if solution meets goal) and representation of information (represent solution). The latter process, representing solutions in external memory in the form of sketches and writings is essential in design.

Conclusions

Akin's approach to design processes focuses more on the components of the design process. Rather than identifiable stages in the process, the operations can be observed anywhere in the process. Sequences of processes constitute methods, the same TOTE mechanism operates on a primitive level and on the level of subgoals. The large body of domain knowledge is dealt with by an interaction between the regulation of control process and the other primitive processes. The regulation of control process decides on which subproblem to attack next, etc.

The research Akin carried out aimed at characterizing designer's behaviour in the terms defined by the processes, and to look if the methods or process sequences can account for the observed behaviour. His data included both recordings of subjects verbalizations and notes and sketches made. He finds the five primitive processes sufficient to codify design behaviour. However he also suggested that the results should be verified both through replication in independent experiments which he leaves to other researchers and by means of a computer program based on the structure of a design information processing system to simulate designing behaviour.

3.3 Hamel (1990): On designing by architects

Another model of the design process has been developed by Hamel (1990). Hamel also aimed at a descriptive psychological model of the architectural design process. According to Hamel (1989) Akin followed too rigidly the research paradigm. He argues that protocol analysis becomes more fruitful as more prior knowledge is available to score the categories. Furthermore, the model should have been empirically tested by scoring still more protocols.

Hamel then developed his own model, in which he also incorporated the ideas of Anderson (1985), Elshout (1976) and DeGroot (1965).

Representations

Hamel adopts the view of memory units or chunks stored in long-term, short-term or working memory. As an organizational principle, he adopts the notion of schema, described for instance by Anderson (1985). While chunks are rather small units of knowledge, schemas are large complex knowledge structures for storage of meaningful information about objects or events. A schema can be thought of as a set of features. The representation of an object, event or task takes place by specifying the features. Schema's are hierarchically organized and interrelated. They can hold procedural as well as declarative knowledge.

Everything a subject can tell about the state of the problem he is dealing with is called the problem conception (after DeGroot, 1946/1965). Hamel adopts the view of Elshout, Wielinga and Breuker (1984). They asserted that all the declarative knowledge about a problem is organized in a schema, which is called the problem conception schema. When a problem is encountered, related information, possible solutions as well as methods to attain a solution, become activated in memory,
for example some features of the schema regarding typical characteristics of design problems get their values while reading the brief. The problem conception schema can be compared to the problem space in problem solving theory. An important function of the problem conception schema is that it permits easy activation of information that temporarily was out of focus.

The procedural knowledge is thought to be represented in a task schema, according to Hamel the problem solving process is controlled by this schema. Hamel’s model consists of still more schema, which will be discussed in the next paragraph.

Processes

Hamel interviewed architects to identify the basic activities an architect has to perform. These are: gathering information, decomposition of the problem, finding partial solutions, synthesizing the partial solutions, and moulding the product of the synthesis into something that is ‘architecture’.

After identifying the basic activities a designer has to perform, Hamel incorporates these activities in a psychological model. The model consists of a nested structure of schemas. The schemas in Hamel’s model are more then knowledge structures, they contain the sequence of activities that are to be carried out. In this respect, schemas resemble scripts (Schank & Abelson, 1977). The schemas are:

**Problem conception schema:** This schema holds declarative knowledge about the design problem.

**Task schema:**

**Analysis schema:** The schema comprises gathering information, decomposition of the problem and finding partial solutions.

**Synthesis schema:** Partial solutions have to be combined to form one solution to the design problem as a whole.

**Moulding schema:** This last schema is activated to mould the product of the synthesis into something that meets architectural and aesthetic criteria.

In addition to the schemas, Hamel’s model combines task independent activities: orientation, execution and evaluation, at task dependent levels: analysis, synthesis and moulding. The independent activities appear at each level, furthermore the dependent levels are nested.

Orientation at analysis level means gathering information, decomposition of the problem, finding partial solutions. Execution at analysis level actually consists of synthesis, which in turn comprises orientation, execution and evaluation. In this stage the partial solutions are to be combined to form a solution for the design problem as a whole. However, the result of this stage is only something that does what it is supposed to do and still has to be moulded into a design which meets architectural, aesthetic criteria. This moulding in its turn also contains orientation, execution and evaluation.

The model postulates the order of the four levels and within these the order of the three categories, orientation, execution evaluation. From the model a synthetic protocol is deduced. The synthetic protocol is what the model would say and do if it designed thinking aloud itself. Hamel used three protocols to test and ameliorate the synthetic protocol. Hereafter he analyzed twelve additional protocols in order to test the model. After a thorough analysis of the data Hamel concluded that in spite of minor exceptions the model is an adequate description of the design process (Hamel, 1990).

**Conclusions**

Hamel’s model is more about activities on task performance level, and less about the actual
information processing that takes place on representations of the designed product. The large amount of domain knowledge is taken care of through organization of knowledge in schemas, and through decomposition of the problem in subproblems. Control of the process is ensured by the task schema.

Although the model describes recurring cycles of orientation, execution and evaluation, these cycles concern different levels or different subproblems. All the activities belonging to one schema have to be accomplished, before going on to the next schema. In theory, moulding for example, cannot begin until the synthesis of the subsolutions has taken place. The model does not permit large steps back, for example when analysis and synthesis alternate. When alternation of analysis and synthesis is observed in the protocols, Hamel associates this to incomplete analysis, underestimation of the difficulty of the task etc. However, it can be questioned if uncompleted stages and steps back to earlier schema are aberrations in task performance, or on the contrary represent essential loops in the performance of the design task. In other words, although the model has been tested empirically to a certain extent, it describes an ideal order of activities whereby exceptions to this order are interpreted as shortcomings in the designer’s processes.

3.4 General conclusions: comparing models of the design process

Reviewing the literature provided some insights into the views on the design process. The models presented come from different backgrounds, architectural and psychological. However, they have much in common with respect to the assumptions and theoretical framework. All three models are based on the idea that designing can be regarded as problem solving. Arguments were presented in favour of this idea. Furthermore, they stress information processing aspects of the task. Finally, they take into account the limited processing capacity of human memory. In spite of the similarities with respect to their points of departure, the models do also differ on some aspects. Similarities and differences will be discussed. Especially, attention will be paid to the way in which the models deal with design as an ill structured problem, involving a large amount of domain knowledge.

Naming phases

In studying well structured problems that do not require much prior knowledge, no phases in the problem solving process are distinguished. In this kind of problems, it is possible to create an appropriate problem space containing all information relevant to the problem. Problem solving then takes place by search in the problem space, subgoals are set, and finally the goal state or solution is attained. When one would follow rigidly the paradigm, design could be studied in the same way by presupposing a process from start (the brief) to finish (a design proposal). This approach is found in Akin’s conception of the design process (see Figure 1). Subproblems are solved one after the other, but not independently of one another: the solutions of subproblems are taken into account in solving subsequent subproblems. Although Akin does identify different primitive information processes, he does not indicate different phases in the process. The primitive processes can occur anywhere in the process. He does propose methods which consist of sequences of processes, but again no special time or order is defined for the methods to occur.

On the other hand, some researchers distinguish phases in the process. They adopt in part the view of architects. Architects themselves broadly define three stages: analysis, synthesis and evaluation (see for example Boekholt, 1984 for an overview). According to these theories, analysis, synthesis and evaluation constitute a cycle which is observed repeatedly during the process. For instance, after evaluating a design proposal the designer may decide to reconsider certain aspects of the problem, in which case he returns to the analyzing phase. The psychological models provide a
closer look at the different phases. The phases are characterized by the kind of activities that take
place, and the product that defines the end of a particular phase. What phases are distinguished in the
presented models? In Figure 1 the models are presented schematically. The main aspects of the
models are displayed in order to make comparisons between the models. For this purpose, other
aspects, e.g. the existence of feedback loops, are considered less important. Some remarks on these
aspects will be made at the end of this section.

Akin

Boekholt

Hamel

Problem: $P$
Subproblem: $-$
Decision: $ightarrow$
Possible solutions of subproblem $X$: $\bigcirc$ or $\square$
Possible solutions of subproblem $Y$: $\bigcirc$ or $\bullet$

Figure 1. Three schematic models of design problem solving

The design process begins by defining the problem space in which the problem solving will take
place. The problem is stated, additional information is gathered, relevant subproblems are identified. These activities correspond to the first two phases of Boekholt, the problem is defined, the difference between the initial state and the desired state of affairs is clearly defined, the problem is decomposed in subproblems and knowledge about starting points is available. In Hamel's model, this first phase consists of activating the problem conception schema and the task schema for design. Furthermore Hamel speaks of analysis: gathering information, decomposition of the problem, finding partial solutions. Analysis is achieved when solutions to subproblems are found (see Figure 1).

Subsequent processing is aimed at developing a solution to the design problem. In Boekholt's model a number of essentially different possible or variant solutions is generated. Whereas in Hamel's model the partial solutions are combined to a 'box which does what it is supposed to do'. Combining partial solutions is taken care of by the synthesis schema (see Figure 1).

The final phase of the problem solving process should produce a solution to the entire design problem. In Boekholt's model the possible solutions are evaluated. An optimal solution is chosen. This evaluation can provide new insights in the problem, the architect then returns to earlier phases to incorporate these ideas in the starting points. The final activity in Hamel's model consists of 'moulding' the solution into 'architecture'. The product of the moulding phase is a solution which satisfies architectural criteria. In this view of the design process each phase has to be accomplished fully before processing can go on in the next phase.

In summary, according to Akin, an architect works towards a design solution which is gradually developed as subsolutions are integrated. In Boekholt's view, an architect produces essentially different variants and evaluates these. In Hamel's model partial problems are solved and the partial solutions then combined to form a solution to the design problem as a whole. The act of creating something that is art is treated as something that happens only at the end of the process once all practical problems are solved.

Finally, Figure 1 also reveals some weaknesses of the models. With Akin, the order in which subproblems are solved becomes very important, subproblems are not solved independently of the results of earlier processes. In the case of Boekholt, it must be kept in mind that it is virtually impossible to consider each and every possible solution. There will be solutions that drop out some how along the process. Finally, as far as Hamel's model is concerned, the synthesis activities can be very difficult when incompatible subsolutions are encountered. In addition, it remains unclear how the moulding steps can be fully separated from the rest of the design activities.

**Representations and processes**

Phases as described above provide a general characterization of the process at a macro level. At a micro level, design representations have to be manipulated. Boekholt describes this activity as the generation of information systems, which are hierarchically organized, in the form of inter-related images and pictures. New information structures result from combining known information elements or images in the mind. The process by which information is combined is referred to as the elementary operations cycle. It's operations roughly correspond to the phases that are distinguished in the entire process. In other words, the same operations, formulating the problem and starting points, generating and evaluating variants, are observed both when considering manipulation of information structures and in considering the entire process.

Akin mentions a verbal-conceptual and a visual mode of representation. He does not however specify further how processing of verbal and visual material takes place. The state of the problem at hand is represented through a node-link graph. A node contains tokens, like 'site', 'building', etc, and a link represents a relation between tokens, such as 'has', 'is' etc. The problem as such is represented in a structured (hierarchical) way, as a function of the parts of the object under
examination. The processes that act on these representations are the five primitive processes which were already discussed. One sequence of processes, the generate-and-test method, resembles the 'elementary operations cycle' of Boekholt. This method consists of generating a partial solution, testing if the partial solution meets the goal and representing the partial solution.

According to Hamel, processing takes place by combining memory units into larger structures. However, his model only specifies the activities that the architect performs. These activities are not further defined on a more elementary level. The activities are the primitives of the model. Hamel gives two arguments. First, the fast elementary information processes are not likely to be verbalized, and therefore will not appear in the protocols. The fast automatic processes are considered the building blocks of the activities analysis, synthesis and moulding. Secondly, the acts of the designer are not represented in the model as mental acts. A mental act is every unique configuration of elements that can be in short term memory during problem solving. For simple tasks it is possible to give the whole set of possible configurations that can occur during the course of problem solving. In design, such a set of all possible mental acts would be too large. Hamel therefore developed a model describing the activities of the architect.

In summary, Boekholt stresses the importance of developing different solutions by combining information or images to form new structures, whereas Akin pays attention to the information processes in design, and Hamel based his work only on the activities of the architect.

**Domain knowledge**

In the models of the design process, domain knowledge is consulted in a serial fashion. The decomposition of the problem into component problems makes it possible to concentrate on parts of the knowledge at a time. Boekholt identifies levels and aspects to section the problem, the architect has to learn to quickly decide on the number and sort of subproblems which have to be considered. Sectioning in subproblems, solving those and combining the solutions is also a way of dealing with large quantity of knowledge in Hamel's model. In Akin's view solutions of subproblems are integrated along the way, like a serial process where subproblems are encountered and solved using the adequate knowledge, working towards a general solution. Internally, the design knowledge is represented hierarchically in chunks. Both Akin and Boekholt stress that design benefits from representation of information in a visuo-spatial mode.

On the other hand, Bhaskar and Simon (1977) stressed the need of specific procedures to be able to handle the domain specific information. A task schema for the design process fulfils this need in Hamel's model. The task schema contains procedural knowledge concerning design in general. This schema is a script-like sequence of activities, and guides the entire process, evoking still other schema for analysis, synthesis and moulding. The schemas contain task dependent knowledge for designing.

Akin posits a regulation of control process to take care of the large problem. Akin argues that productions are the ideal form for representing procedural knowledge in design. Boekholt does not specify procedural knowledge, but he states that the architect has learned how to deal with design problems through experience.

**Ill structuredness**

In general, ill structured problems are dealt with by dividing them into a number of smaller well structured subproblems. However, there are difficulties that arise from solving the problem in this manner. Interrelations among the various well structured subproblems have to be monitored. Solutions to particular subproblems can interfere with each other. Finally, the overall problem remains ill structured, in the sense that criteria to decide whether a solution is found are unclear. How does an architect deal with the ill structured design problem?
Boekholt argues that a hierarchical sectioning in subproblems will preserve relationships between the subproblems. Different solutions are developed. Evaluation of essentially different solutions provides a way of dealing with vague criteria.

According to Hamel, an architect learns through experience how to decompose a problem, and how to deal with interrelations between the partial solutions. In addition, architects 'know' what architecture is, vagueness of the aesthetic criteria then becomes a matter of personal style.

In summary, in design there is no best solution, there are many possible solutions and problem solving in design means searching for an optimal solution.

Images

Architects often refer to the manipulation of pictures in their head when talking about their images of the object they are currently working on. Both Boekholt and Akin stress the importance of images with regard to the process of developing a design solution, as well as with regard to the representation of design knowledge in memory.

In cognitive psychology the question has been addressed whether image representations have a different format from that used in other representations. A broad distinction which has been made is between verbal descriptive and spatial pictorial, or proposition and image models of representation. Propositional representations are language-like entities that describe or assert facts. Various propositional models have been proposed (e.g. Collins and Quillian, 1972) which have subsequently stimulated much discussion and research. On the other hand, considerable empirical evidence has also been gathered concerning imagistic models (Kosslyn, 1980).

The distinction between images and propositional representations rests on the difference between depiction and description. Kosslyn illustrates this with the example of the representation of a sentence (see Figure 2). Propositional representations do not possess the properties of imagistic representations and vice versa.

**Figure 2.** Privileged properties of propositional and imagistic representations (taken from Kosslyn, 1980).

Abstract spatial isomorphism means that any portion of a representation (an image) is a representation of a portion of the represented object. In addition, it is impossible to depict shape without depicting orientation and apparent size, and the internal symbols used to represent an object are not arbitrarily related to the object. Abstract surface-property isomorphism means that images also depict information about the appearance of surface properties of objects such as texture or colour.
A great deal of research has been done by Kosslyn who tried to discover what images are, how they arise, when they are used, and what it means to look at and manipulate visual mental images. Introspection was originally a method for studying images, later on research concentrated on the "quantification of introspection", the measuring of reaction times as observable consequences of the observed internal state or event. Kosslyn concluded that visual mental images do play an important role in cognition.

Imagery also appears to be important in inference making. According to Lindsay (1988) images are so called inference making knowledge representation systems. An inference making knowledge representation yield information that has not been provided directly to it. They make inferences without the use of explicit rules of deduction but simply by virtue of the properties of the knowledge representation system alone.

Obviously, external images and propositional representations can be compared in the same way. For example, Larkin and Simon analyzed diagrammatic and sentential external representations. They speculate that mental images could play a role in problem solving analogous to the role played by external diagrams. By virtue of its properties, information is made explicit in the course of constructing a mental image, as it is when drawing a diagram (Larkin & Simon, 1987). The difference between diagrammatic and sentential representations will be discussed in more detail in the paragraph about information presentation.

Although images and image processing appear to be important in design, they did not receive much attention in the models discussed.

4 Information and knowledge in design

4.1 Kinds of knowledge

The design process has been described as a problem solving process involving large amounts of domain knowledge.

A distinction can be made between declarative knowledge and procedural knowledge. Declarative knowledge comprises the facts people know. Procedural knowledge comprises the skills people know how to perform (Anderson, 1985). An example of declarative knowledge in design is a fact such as 'a house comprises a living room, a kitchen, bedrooms and a bathroom'. An example of procedural knowledge in design is a skill such as drawing walls, windows etc.

The architect has acquired a large body of declarative background information: the general body of knowledge that is shared by design professionals (Akin, 1986). In addition, the architect has acquired design skills through education and practice. According to DeJong and Ferguson-Hessler an effective knowledge repertoire also contains strategic and situational knowledge in addition to procedural and declarative knowledge (DeJong, 1986, Ferguson-Hessler, 1989). They studied these kinds of knowledge with respect to solving physics problems. Situational knowledge is necessary to recognize problems in a particular domain, and is important for the selection of relevant declarative and procedural knowledge in memory. In design, knowledge of problem situations is necessary to distinguish for example the designing of a house versus the designing of an office building. Strategic knowledge is a more general kind of knowledge, it contains the actionplan for accomplishing the task. For example the designer has to gather information, decompose the problem, solve component problems, bring all subsolutions together. This is the kind of knowledge in architecture that was incorporated in Hamel's model (see section 3.3).
The four kinds of knowledge form the knowledge base for a particular domain, and is contained in so called cognitive structures.

4.2 Information retrieval

Designers typically do not have all the knowledge they need to solve a particular problem stored in long-term memory. Seeking additional information is an essential component of the design task. When the architect fails to find certain information in long-term memory, he will look elsewhere (Akin, 1986).

Some of the knowledge becomes active while studying the design brief which is the basis of a design problem. The design brief specifies the requirements the designed product has to fulfil and the resources of a client. The background knowledge and the design brief jointly provide an initial problem space in which problem solving can take place.

At the start of the problem solving process the additional information mainly concerns the problem at hand. The designer consults the brief and the client. Hamel identified the gathering of information as the first activity in the design process. New information has a large impact in the beginning of the process. Later on it will be more difficult to incorporate new ideas. Therefore information pertaining to decomposition of the problem, solving subproblems and combining subsolutions will be most important in the early phases of process, in the analysis phase (Hamel, 1990). We find the same need for information in earlier phases in Boekholt's model. In formulating the problem and 'starting points' the architects must try to consider everything that is important.

During subsequent processing, the information needed will be more specific. The information deals with the solving of particular subproblems. For example, whereas the architect in the beginning of the process might want to know general requirements for the project, later on he needs exact measurements to meet the requirements. The architect has to search for missing declarative information by consulting experts, books etc.

In the final phase much less information is needed, the final solution is elaborated. This elaboration depends much on personal style. The solution is judged against criteria that were established at the outset. However new hereto unknown criteria can also appear (Boekholt, 1984).

In inspecting protocols of architects Hamel scored the kind and source of knowledge the architect used. The additional information in the design domain involved the following topics (Hamel, 1990):

The situation (51%): features and characteristics, measures and dimensions, traffic, circulation, orientation, users.

The assignment (5%): budget, number of users, management of the building.

The requirements (41%): functions, criteria and qualifications, behavioral and technical requirements.

General information (3%): norms, rules and regulations, behavioral and technical data.

The first three categories have to do with the problem at hand. The designer needs this information to get a full picture of the problem. Knowledge of problem situations in design guides the architect, and helps him to ask relevant questions about the project. The fourth category represents missing declarative information in general. According to Eastman (1980) this distinction between project dependent and project independent (general) information is important when considering databases for design.
Architects get their information from different sources. In Hamel's study (1990) the sources were: material coming with the assignment 37%, own knowledge 31%, communication with experimenter (or client in more realistic settings) 24%, assumptions 7%, literature 1%. Hamel observed that architects mainly used their own knowledge and the brief in solving the problem (Hamel, 1990). However, effects of the experimental situation could have influenced relative percentages. Sources of information depend on the situation and the particular design problem that is studied.

In short, it can be concluded that in elaborating problem, the architect mainly needs project dependent, declarative information; he gets this information from the client and the brief. Later on, during problem solving, the architect needs project independent, declarative information. He possesses already parts of this information, and he can consult books and experts. Finally, in refining the solution, more aesthetic considerations become important.

4.3 Presentation of design information

Looking for additional information has been identified as an essential characteristic of the design process. However, in Hamel’s results, only 3% of the information requests concerned general information, and only 1% of the information requests were looked up in books. Indications that architects do not always use available information are also found elsewhere in the literature (Goodey and Matthew, 1971, Newland, Powell and Creed, 1987, VanAndel, 1988). So, while information retrieval during design is judged important, it does not always take place. What are the factors influencing information retrieval during design?

On the one hand, the lack of information retrieval is attributed to characteristics of the designer. Lack of information use is interpreted as a communication gap between researchers and designers (VanAndel, 1988). Researchers and designers differ in a number of respects. For example, whereas researchers aim at an accumulation of knowledge, designers focus on finding a solution to one particular problem. In other studies, the effect is attributed to learning styles of architects. For example, Newland, Powell and Creed (1987) discuss designers’ selective information handling.

On the other hand, characteristics of the information and its presentation influence information retrieval. Research reports presumably do not have the proper format for designer’s to understand (Hamel, 1990). Others researchers mention variables like applicability, clarity, use of visual material (Goodey and Matthew, 1971, Hamel, 1990, VanAndel, 1988). Two format aspects of design information presented will shortly be discussed: the use of visual material and the structure of the information.

Text versus pictures

Problem solving in design involves manipulation of images in the mind. What is the relation with the presentation of information using visual material?

Larkin and Simon (1987) analyzed sentential and diagrammatic external representations. Sentential representations are sequential like propositions in a text. Diagrammatic representations are indexed by location in a plane. The fundamental difference between the two is that diagrammatic representations preserve explicitly information about topological and geometric relations, while sentential representations do not. Two concepts are important to Larkin and Simon’s analysis. Informational and computational equivalence. Two representations are informationally equivalent if all of the information in the one is also inferable from the other, and vice versa. Two representations are computationally equivalent, if they are informationally equivalent and in addition any inference
that can be drawn easily and quickly from the information given in the one can also be drawn easily and quickly from the information given explicitly in the other, and vice versa. In order to compare diagrams and words one has to consider both the data structures and the nature of the processes that operate on them. Larkin and Simon looked at three kinds of processes. Search processes, recognition processes and inference processes. They concluded their analysis of examples from physics, and geometry by the observation that search is expected to be quicker on diagrams as compared to lists of propositions, recognition is highly sensitive to the exact form in which the information is presented, visual elements therefore will be recognized quicker in a diagrammatic representation. In addition, the ease of recognition is affected by what information is explicit in a representation and what is only implicit. Finally, inference processes are expected to be independent of representation if the content is equivalent. Fast inferences usually result from fast search and recognition processes.

Conclusions: diagrams can group together all information that is used together, thus avoiding large amounts of search for the elements needed to make a problem solving inference. Diagrams typically use location to group information about a single element, avoiding the need to match symbolic labels. Diagrams automatically support a large number of perceptual inferences, which are extremely easy for humans (Larkin & Simon, 1987).

Although use of visual material is generally recommended in presenting information to designers, there is no empirical evidence for the efficiency of images to convey information.

**Structure**

Information can be structured in different ways. A linear structure is the structure of conventional textbooks. Information can also be hierarchically structured from general, pertaining to a problem as a whole, to specific, pertaining to small subproblems. Or alternatively, the information can be hierarchically structured according to 'problem schemata' in the domain. For example, information can be structured according to levels (room, building, neighbourhood), and aspects (construction, use and maintenance) (Boekholt, 1984). A special structure is a hypertext structure which resembles a semantic network of concepts. Some authors claim that hypertext permits a structure that resembles closely the structure of knowledge in the mind. "The associative form of storing information seems to conform to the way that human memory is organized" (Chignell and Hancock, 1988, p. 983). The way in which the structure of information influences information retrieval will be the subject of a future report.

**4.4 Future actions**

The design process was studied in the literature in order to be able to study the role of information in design. Information retrieval is important during the stages in the design process. However, it was observed that designers do not always use all the information available to them. The presentation of design information should be further studied. Some preliminary remarks were made about the use of visual material, and the structuring of design information. A future report will deal with these two aspects in more detail. Especially, the role of hypertext in presenting information will be further elaborated.
References


