The University of Calgary

Sketching in Design and CAID: A Theoretical Exploration

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To my wife

Yael

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Abstract

The goal of this work is to suggest ways of improving design representations in computer environments in order to support creative design work.

In order to achieve this goal, the following issues are explored:

1) the connection between computers and creativity,

2) the nature of design problems,

3) the characteristics of design processes used to solve these problems,

4) the knowledge and information involved in design, and

5) the way this knowledge is represented to facilitate creative design exploration.

These issues are explored from both theoretical and empirical perspectives. A review of theories from literature is presented, then a description of an empirical study; the findings from these two approaches are used to construct a model which suggests a new way of describing design, based on the hierarchical order common to individual design problems, the processes of solving them, and the way they are represented. The model is used to analyse a design process and depict the settings of creative instances within it.

The review of theories on design practices and their representations reveals that design sketching is not only a means for representing data, it is also a means of enhancing design thinking itself. This issue requires further study and is not completely resolved in this project.

The conclusion of this work suggests that design sketches offer unique abilities in representing design. Therefore, any representation scheme in CAD should attempt to incorporate these abilities in order to support creative design practice.

1. Introduction

1.1 Goals and Motivation

Computer Aided Industrial Design (CAID) tools are Computer Aided Design (CAD) tools specially suited for industrial designers. CAID systems are intended to fit the unique characteristics of industrial design work. This definition is not useful for developing a CAID tool, because it does not give any detail as to what is required from such a system, or any specific characteristics. This project includes a discussion about the specific characteristics of industrial-design practices and suggests a possible direction for development of CAID tools.

In this project, the term *design* has the following meanings:

1) *Design* is the act of creating and representing things (i.e. objects or procedures). Combining design definitions from Gero and Rosenman (1996), and from Schön (1984), yields the following: To design is to purposefully create and represent new things. *Design* activity determines and defines *design* as a practice[1].

2) The term *design* (as an object) refers to the "thing" being developed during a design activity. The "designed entity" (Goldschmidt, 1993), or the outcome of a fruitful design process, is a *design*.

The above terms are global and do not refer to any specific type of design. Industrial design is seen as the process of designing objects (products) under constraints of usability, manufacturing, marketing, and culture.

Design is a complex activity involving a variety of components and aspects (Goel, 1995; see also Appendix A) that cannot be covered in the scope of a single study. This study concentrates on creativity in design, and the relationship between design processes and the representation schemes used in them. The goal of this study is to suggest new and improved directions for using computers in supporting creative design activity. This study

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[1] The term "practice" is used in place of "profession", because design has many variants that are not necessarily all professions. A practice is often seen as profession only if it involves professional accreditation, which is not relevant to the objectives of this study. Fashion-design is different from industrial-design, even though both are design practices. This clearly shows that design is not describing a single practice.

starts by studying the limitations and strengths of traditional[2] design practices from a number of perspectives and continues with analysing how these practices can and should be supported by computerised aids. This project includes a theoretical exploration as well as an empirical study of "design-by-sketching" (Lawson, 1990); it does not include evaluation and analysis of existing CAD tools.[3]

This document includes four parts: an exploration of creativity with respect to computers, a literature review, empirical observation, and analysis; all of which lead to a new descriptive model of creativity in design, with implications on the development of CAD systems for industrial design.

This work attempts to improve both CAID and general CAD tools by providing some suggestions for representing design information in computerised environments, and for interacting with these representations. I believe that current computerised representation schemes are a major cause for difficulties of "operating" CAD tools; thus, this work examines methods and implications of representing data for design purposes. It tries to determine what needed qualities are missing in CAD that could improve its ability to actually aid design work creatively. I see my first task to be the exploration of the interaction between designers and the traditional design sketches, and to suggest some directions for re-formulating computerised representation schemes in a way that can aid design work, especially the parts involving creative exploration.

It seems that most CAD systems were developed with the assumption that designers have a detailed mental image of their designs, and all that is required to create a detailed and accurate representation of these designs is to code them into the system. I side with the approach taken by Goldschmidt (1992), Hutchins (1995), and others, who suggest that external representations, such as design sketches, serve as an interactive dialogue between internal and external representation schemes. Goldschmidt calls this quality "interactive imagery" (1992, p. 199) and Hutchins calls it "external memory aids." The major difference in perspective between this approach and that of current CAD systems is that existing CAD tools expect the designer to have a design finalised, and ready to model it into the system. I suggest that the creative design work can only occur if the exploration is performed in parallel with representation, and that using CAD for such exploration is difficult because working with CAD requires designers to devote much attention to the

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[2] Goldschmidt reports that designers have used sketching on paper as a means for representing the design thoughts and ideas ever since paper became an affordable commodity in the Renaissance (Goldschmidt, 1990).

[3] This project includes a study of existing CAD tools with their advantages and limitations, but is not based on analysing the use of such systems.

translation of design ideas into the CAD system. This requires them to separate between expressing design ideas and perceiving the outcome. This may disturb the dialogue between the designer and the evolving design, and breaks the useful perception-action cycle.

Fundamental design practices include development and representation of new design solutions, whether a consumer product, a garment, or a building (Lawson, 1990). These representations are created for the following reasons:

1) To store (archive, remember) the design state[4] or other relevant data.

2) To serve as a visual (or other) calculation aid (Hutchins, 1995).

3) To communicate the design (to other people or devices).

I would expect a CAID system developed using the recommendations of this study to extend traditional design sketching (on paper) by facilitating the process of sketching with a computer. This study is based on the understanding that design-by-sketching employs human capabilities of visual thinking, i.e. the analysis and calculation of image information using high levels of perception. Most studies of the interaction between designers and their sketches have explored the cognitive and perceptual processes of this interaction; none, however, include analysis of sketching in context and with attention to more complex and abstract levels of design activity. This study reviews studies of various aspects of interaction with sketches and suggests a new perspective on studying design sketching, involving consideration of perceptual and cognitive processes used for creating and modifying sketches. This is done in respect to the model proposed below in Chapter 5, showing the detailed descriptions in a context of the entire process, with mapping of different levels of abstraction in the time, design domains, and representation schemes used. Another objective of this study is to examine the possible connection between "emergent" instances of new concepts and contributing factors in the sketching environment. I consider these factors to be essential for the design of a CAID system that supports sketching in a useful and usable fashion. This study includes an observation of paper sketches because they are common among all members of society and are considered to be essential to any design professional practice (Goldschmidt, 1991).

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[4] The definition of "Design State" is based on Akin's term (1987) "goal states" (p. 23) that refer to the desired final state of the design process. Design State describes the evolving state of the design, going from problem to solution. It is important to note here again that design problems are often ill-defined; therefore, they do not have a clear definition and frequently do not have a single solution.

Traditional design relies on sketching (Lawson, 1990), whereas CAD uses other means of representing shapes and ideas. CAD seems to be limited in its efficiency, especially in its ability to support creativity in design work (Hennessey, 1994). Computer systems are automated mechanisms based on well-defined algorithms created in advance by computer engineers and programmers, and based on reoccurring series of events inherent to the work procedure. Therefore, they perform most efficiently when repetition is involved. In contrast, one of the main goals of design is to create and develop the new. This makes the concept of CAD tools somewhat of an oxymoron, since CAD is an attempt to marry the repetitive nature of computers with the unique and innovative nature of design. Another reason for CAD's inability to support creativity originates in the selection of schemes used to represent information in design, and their limitations compared to the traditional sketching. Studies (Hennessey, 1994) have shown that design sketches are much more efficient than current CAD tools for facilitating design exploration. I explore the reasons that make traditional sketching more productive compared to CAD tools.

This project does not attempt to study all aspects of CAD; it is rather an attempt to explore possibilities of facilitating and perhaps extending creative exploration with computers. It concentrates on the study of visible design elements—design representations, sketches, and notes—produced throughout the process. This project is an attempt to gain better understanding of the role design-sketching plays in traditional design processes. This understanding can help us describe the characteristics of representations most suited for the variety of situations in the creative design process.

After describing the objectives of the study, let us review the methodology used to achieve them. The following section describes, in general terms, the methods used in the project.

1.2 Methodology

The understanding of CAID development during initial stages of this project suggested that when design is observed in a high level of detail, it is possible to detect some reoccurring operations common to most designers. Once these detailed operations are recognised, they could be facilitated in CAID systems and lead to improved tools. This concept proved to be incorrect during the observation. It was found that common behaviour is found only at lower levels of detail and when the situation is considered from higher levels of abstraction. The more detailed the observation, the fewer common operations can be found.

This study was composed of the following five processes:

1) Review of theories describing design work—with emphasis on creative exploration in design—in an effort to understand how sketching mechanisms support creative design processes.

2) Observation of actual design sessions in order to explore design sketching activities.

3) Review the design theories in light of the observation, and construct a model useful for analysing the observed design sessions.

4) Apply the model to the design observations.

5) Study the results of the analysis and apply them to CAID development.

The most common[5] methodology used for studying design processes is called *protocol analysis*[6] and is based on recording and analysing verbal testimonies taken during or after a design session. For this study, designers were instructed to design a wearable computer for auto technicians, and were asked to verbally express their thoughts or "think aloud" while designing. These sessions were videotaped, and the recordings were later processed to produce protocols of verbal testimonies, verbal descriptions of participant's actions, and visual records describing the appearance of the drawing surface at each described moment. These protocols were then coded and qualitatively analysed. A detailed description of this analysis is provided in Chapter 4.

The observation in this project was intended as an exploration of design activity, and was not an attempt to prove a hypothesis. During this observation, a model was constructed as a tool for organising and analysing the data. The model was found to be useful for analysing and describing design processes; it creates a new way of seeing design activity as a combination of perspectives used for interacting with designs, schemes used for representing them, and the level of abstraction used during the interaction. The model describes design activity as a graph with four dimensions: Design domains, Time, Abstraction levels, and Representation schemes. This model was then used for visualising design activities. The combined understandings from literature (Chapter 3), from the results of the observation (Chapter 4), and then the understanding gained from the visualisation using the model (Chapter 5) was used to draw conclusions about the required characteristics of representation schemes and methodologies useful for supporting creative exploration in design.

Many researchers (e.g. Lawson, 1990; Rowe, 1992; Simon, 1969) describe design problems as ill-defined, ill-structured, and open-ended. Their common understanding

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[5] Protocol analysis was the primary research method used in design research during 1996–1997 according to publication lists of the Design Research Society.

[6] The use of protocol analysis is described in Ericsson and Simon (1984). A series of studies that use protocol analysis for studying design activity is given in Cross et al. (1996).

suggests that the ill-defined and ill-structured nature of design problems eliminates any possibility of prescribing design solutions to design problems *a priori* (e.g. Akin, 1987, p. 21). Examining these characteristics of the design problem may suggest that design processes—processes of solving design problems—are difficult to describe in an organised fashion.

This project attempts a different approach to describing design processes. Instead of describing a design process only on the basis of the problem it comes to solve, this project combines an examination of the design problem with an examination of the way the problem is perceived by the designer and the way it is represented throughout the design process. In other words, this project suggests a model for describing design activity as a combination of four dimensions: the design domain, the method of representation, the level of abstraction or detail, and time. These dimensions are described in further detail below; at this point, however, it is necessary to provide their basic meaning.

The *design domain* dimension refers to the focus of attention in the design situation[7]. *Design domain(s)* correlates with certain component(s) or aspect(s) of the design, considered from a certain perspective. (The concept of dividing design problems into their specific design domains is explained further in Chapter 3). For example, when designing a wearable computer, designers should consider various aspects—each traditionally handled by a different expert, such as structural engineering, marketing, or manufacturing. Design domains may also reflect the part of the design being attended to at a given time, from a physical or a functional sense. For example, designers need to attend to different physical components of the wearable computer (i.e. the headgear, the CPU, and the input device), but they must also attend to its different functional components (i.e. interaction devices, power supply, memory, etc.). As demonstrated in this example, designers must often design a single component from many aspects.

The method of representation or *representation scheme* dimension refers to the language, coding scheme, or medium used to represent the knowledge about the design. It is important to note at this point that each representation scheme has design domains it best represents. For example, a conventional production drawing is most suitable for representing mechanical information required for production of specific parts. It is quite useless, however, for conveying the aesthetic values of products.

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[7] Design situation in this document refers to the design problem space at a given time. Several researchers (e.g. Akin 1986; Rowe, 1987) show that design activity is connected to the design problem space as perceived by the designer at a given time. During the initial design situation, designers perceive mainly the problem based on their design brief, pre-suppositions, and personal design style; while during the final stages of their design activity, designers tend to see a much more focused and comprehensive problem-space that includes their design solution.

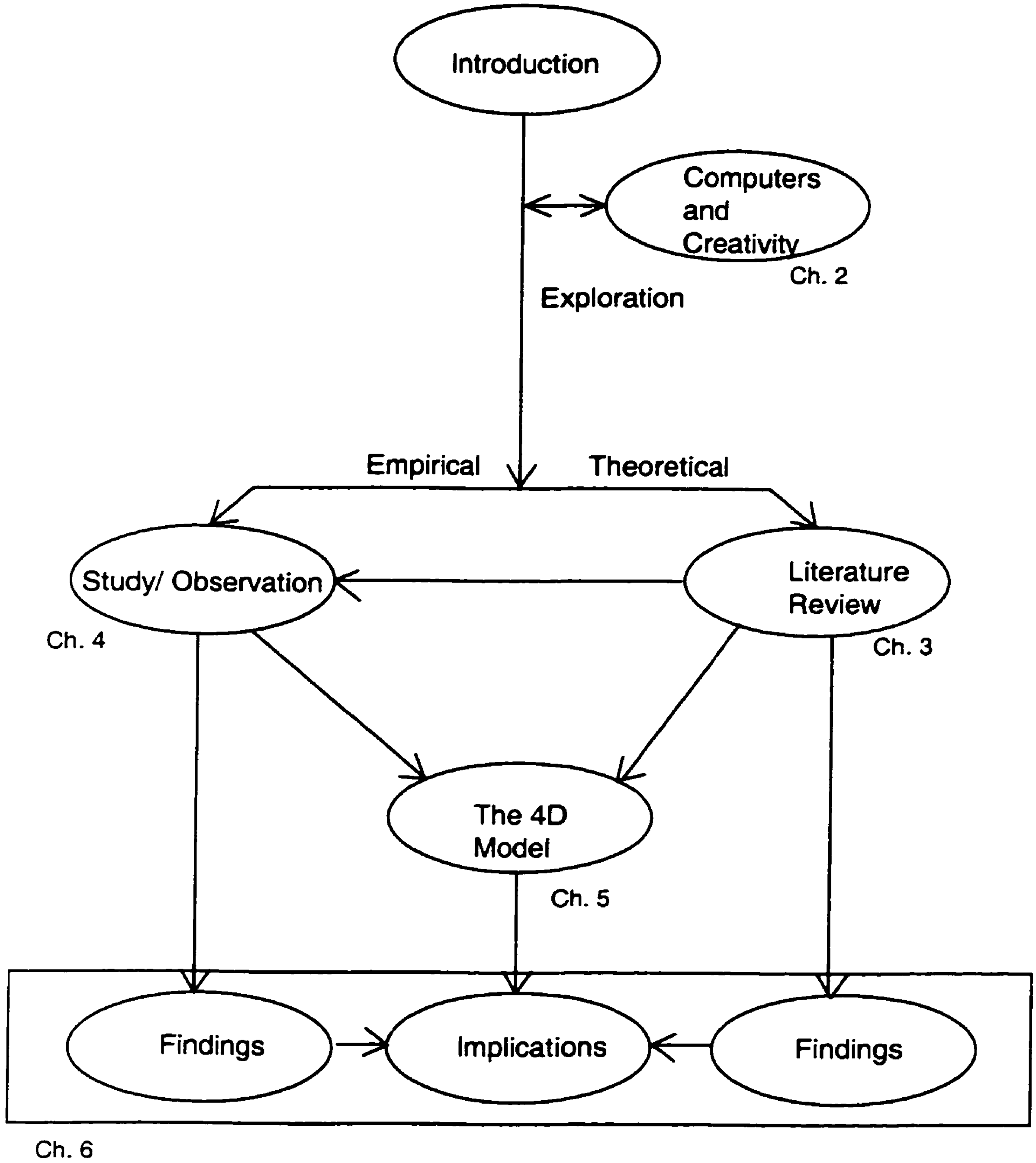
The *abstraction level* dimension refers to the level of aggregation in both the representation and the design domain. It is so named because the higher the level of aggregation (less detail), the more abstract the representation becomes. For example, when we tell experienced drivers to "start the car," they would usually understand what we mean, whereas a beginner might require the following instructions: insert key into ignition switch, check gear position, turn key, wait until you hear the engine starting, then release the key. The term "start the car" is more abstract; it is an aggregation of the list of operations. It is also more open to interpretation, since different drivers have different styles of starting the car.

The *time* dimension represents time flow in the design process. Time itself can also be described at a variety of aggregation levels, ranging from describing the entire design process to describing a single brush stroke made during a design session.

This model (described in greater detail in Chapter 5) shows the settings existing in creative instances. These settings are needed to understand the requirements for allowing or enhancing creativity in design.

1.3 Organisation of the Project and the Document

This project attempts to understand how design is performed traditionally, and how it could be better assisted by computerised systems. The main focus of the work is design-knowledge and ways of representing it and interacting with these representations. This document is structured in the following way: The previous section of Chapter 1 introduced the goal of this project and the motivation for selecting it. Chapter 2 describes the problem of involving computer systems in creative activities; its main purpose is to set the ground for understanding the intrinsic difficulties in using computers to aid creative activities. Chapter 3 is a literature review of design problems and processes with the knowledge involved in them, and the various ways of representing knowledge in design. Special emphasis is placed on design sketches and the way they are used. Chapter 4 describes the observation conducted as part of this project, its goals, participants, methodology, and results. The outcomes of this observation are described in Chapter 5, where a four-dimensional model of design activity is proposed. The conclusions of the entire project, and a set of suggestions for the development of representation schemes in CAD and CAID, are given in Chapter 6.



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2. Creativity and Computers

Enabling and supporting creativity in CAD systems requires an analysis of the factors contributing to creativity, but before we can consider supporting creativity, we need to understand what it means. Reviewing creativity in this project is necessary, because of its pivotal role in design, and gaining a better understanding of creative behaviour may contribute to the general understanding of design behaviour.

Creativity is difficult to define and study, and generally refers to the act of generating, making, or finding of the new. Based on the discussion given in Rassmusen et al. (1995), it is suggested that, when trying to study creativity we face the following problems:

1) A study of creativity can be based on a comparison between two time instances, *before* and *after*. The selection of these points seems arbitrary in time, and does not allow us to study the process of creation because we do not always have the tools to detect the correct instances. When do we consider the instance of creation to be: the moment of possible existence, the moment of recognition, or the moment the idea was expressed or represented?

2) Detecting a creative situation occurs in hindsight, so when we detect an emergent instance, it is often too late to support creativity.

3) The definition of "something new" includes both cases involving a complete creation of something or cases of modification of existing things.

4) When dealing with a modification of an existing thing, how much needs to be modified in order to be defined as a new creation.[8]

5) Scientific study of creativity is limited, because science, which is based on the systematic examination of (past) events, is not equipped to deal with the often unexpected and, therefore, non-systematic happenings in the future.

It is difficult to study the factors contributing to creativity, because creativity includes two processes: exploration and discovery. The debate over creativity started with Plato, who argued that intentional creative search is impossible; that one could not attempt to create something new, since the mere notion of searching for it would require a preconception of its existence. This dilemma is resolved if we suggest that creative search does not have to be completely directed; rather, it can flow dynamically without accurate expectations

[8] This issue is crucial to the subject of intellectual property and patents.

from the forthcoming idea. It seems that creative discovery is only recognised in hindsight and the new idea is identified only after conception.

Emergence is defined as the conception[9] of a new idea or concept, and the instance of emergence is defined as the moment of recognising the idea. For example, a solution to a geometric problem can already exist on the paper even if the designer has not yet recognised it, in which case, it was not yet conceived by him or her, and naturally should not be considered as a creative instance. This is based on the understanding that in many cases in design, solutions may exist as options but do not emerge as solutions until the designer decides to choose them as *the* solution. Furthermore, design often includes a series of creative instances that direct the possible options for proceeding in the search of the finalised design solution. I have chosen to focus my study on the examination of emergence rather than on general creativity, because it includes the time of conception and can, therefore, be related to the design process as a function of time.

Finke et al. (1992) propose a theory that describes the cognitive processes involved in creativity. In this theory, they examine what they call the *preinventiveness properties*, defined as the properties that are often found before—and are believed to support—creative instances. Finke et al. list (p. 23) six different preinventive properties of information structures[10]:

1) Novelty: the unfamiliarity in encountering the new situation.

2) Ambiguity: the range of possible interpretations of a structure.

3) Implicit meaningfulness: a general, perceived sense of meaning in the structure, which enables unexpected interpretations of the information.

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[9] This definition is based on a combination of approaches on the subject of emergence collected in Edmonds and Moran (1997), as well as in Cross (1997), who defines emergence as "the process by which new, previously unrecognised properties are perceived as lying within an existing design."

[10] The paper by Finke et. al (1990) describes cognitive processes in creative behaviour. They examine creativity mostly in combination of graphical elements. They use the term *information structure* to refer to the structures emerging as results of combinations of more basic information elements.

4) Emergence[11]: the extent to which unexpected features and relations appear in the preinventive structure.

5) Incongruity: the conflict or contrast between different elements in the structure.

6) Divergence: the capacity for finding multiple meanings or uses in the same structure.

Finke et al. suggest that preinventive structures are usually visual or spatial images, which, in design terms, translate to two-dimensional (2D) and three-dimensional (3D) sketches respectively. They also note that larger combinations of these structures transform into mental models at a later stage in the process. The common denominator of all these preinventive structures is that they are initially formed without a full anticipation of their resulting meanings.

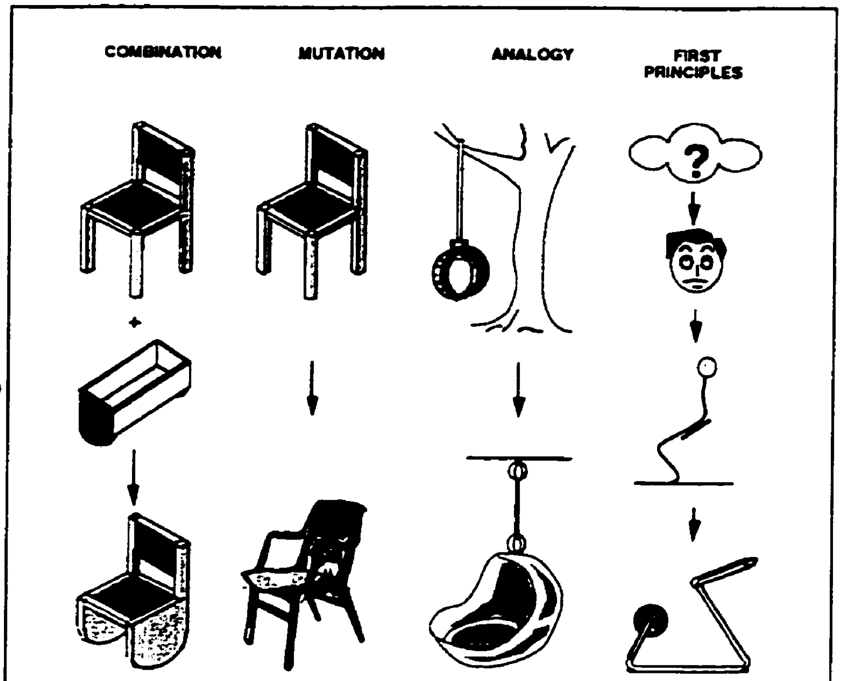

Figure 2.1: The possible procedures leading to emergence: combination, mutation, adaptation and first principles, from Rosenman and Gero (1993)

Gero (1995) studied the subject of emergence in design and the possibility of simulating it in computerised means, basing his model on creativity in humour, and suggested a flow chart in which an emergent concept is a result of a complex object or a combination, assemblage, or composition of two or more inconsistent, unsuitable, or incongruous parts or circumstances. He viewed the representation of these elements as a series of schemata and suggested that the interaction among data elements can lead to one of three options: an expected result; an unexpected, unwanted result; and an unexpected, wanted result, where the latter is a desired case of emergence. However, this model is abstract and generic, and does not specify the required settings for supporting emergence.

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[11] This definition of emergence refers to a characteristic of a structure, not to a process as found in Cross (1997) and Gero (1995).

In an earlier paper, Rosenman and Gero (1993) suggest a descriptive model of creativity in design. They postulate that creativity is a process that involves one of the following procedures taken from the field of artificial intelligence: Combination, Mutation, Analogy, or First Principles. Figure 2.1 shows the examples of creativity involving each of these procedures.

The theories proposed by Rosenman and Gero, as well as Finke et al., are helpful for describing creativity, but offer little help when trying to construct a computerised mechanism to support creative exploration in design. Finke et al. mainly describe creativity in simple tasks, and do not offer a complete explanation for complex tasks like design. Finke's theory is useful in providing some characteristics for a representation scheme (commonly considering representation schemes to be information structures[12]) to support creative behaviour, whereas Rosenman and Gero's theory is useful for describing different types of operations leading to the emergence of new concepts and ideas.

After reviewing some theories regarding operations performed on representations in creative design behaviour, we can now examine CAD's limitation in supporting creative design exploration. The following section reviews previous—and so far not completely successful—attempts of CAD systems to provide support for creative design exploration.

2.1 Existing CAD Systems

How can computers aid design practice? Researchers have struggled with this question since the early development of CAD. The most widely accepted approach was developed by Ivan Sutherland in 1963 at MIT. He suggested that design is best assisted by an enhancement of its structure, and that this could be done by simply applying structure to the objects used by designers during the design process. The best assistance CAD systems could give designers is by providing a mechanism that can help them structure the construction of their designs.

In his Sketchpad system, Sutherland introduced a breakthrough in computer graphics, by allowing designers to create 2D line drawings representing design plans directly on a computer screen by using a lightpen. A system capable of handling 3D "drawings" was generated soon after; this system, however, did not deal with 3D objects as such, rather it used the boundary conditions system[13] (Foley and van-Dam, 1988) developed by

[12] Rosenman and Gero base their theory on the use of *information structures*, defined as a set of information elements governed by a given set of rules and operations. The concept of *information structures* corresponds with the rules applied to representations used in experiments conducted by Finke et al. (1990).

[13] The idea behind the boundary conditions system is that every straight line can be represented completely by specifying its boundaries (i.e. its start and end points). More

Sutherland. The main limitation of this system is that it is not naturally structured for handling curvatures; however, this limitation was solved with the introduction of vector graphic formulation[14] (Foley and van-Dam, 1988). The shift to 3D modelling during the early nineties required a change in approach in CAD development, because the change in object topology allowed for modelling of physically-impossible objects. The solution was to modify the coding scheme and transfer to "solid modelling," where objects are still defined by using boundary conditions, but now the conditions have to comply with some rules, e.g. an object has to be a closed volume to be used as a solid object. Most CAD packages today (AutoCAD, Microstation, I-deas, for example) are based on Sutherland's approach.

The most important role CAD plays in common design practice is in representing shapes, structures, and other mental imagery existing only inside the minds of designers. These representations are then used in many tasks, such as visualisation, analysis, simulation, and production. The biggest drawback of the current approach to representing design ideas is that they require complex modelling processes that require designers to separate the synthesis of design ideas and represent them using mathematical models in CAD formalism. The idea of using mathematical models was first suggested by Sutherland in Sketchpad and was seen as a clear advantage over non-structured paper sketches. This method gives an advantage to the machine—it allows for better, more economical and efficient formulation—but imposes great difficulties on the user because it adds the task of translating the spatial-visual information into a computerised code. The user is expected to communicate with the machine in the machine's own language.[15] This coding task is one of the major reasons for the complexity of operating CAD systems and the steep learning curve required for mastering them. This difficulty is hard to overcome, because design representations may have more than one meaning, and each of them may be associated with a different interaction mechanism.

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complex objects such as 2D polygons can be represented in the same manner by specifying their boundary conditions, which are their vertices or their line segments. Extending 2D to 3D is done by adding another dimension to each vertex, which allows defining any 3D polygram by listing its 3D vertices.

[14] A curve can be defined using the vector graphics formulation by dividing it into segments that are relatively simple. Each of these segments is defined using a polynomial. These polynomials are usually square or cubic, i.e. second-degree or third-degree polynomials, which are relatively simple.

[15] The modelling language is often a type of a scripting language that is not strictly a machine language, but nevertheless requires the designer to "program" the CAD tool in order to create the desired model.

The perceived strength of computerised systems was not consistent throughout the historical evolution of CAD systems. In the early days of CAD, computers were considered to be arithmetic calculation machines. During the seventies and early eighties, with the rapid development in artificial intelligence, it was expected that CAD systems would someday be able to design without human intervention (e.g. Cross, 1977; Negroponte, 1975). Today, CAD is commonly expected to help in performing mathematical calculations and analysis; representing design solutions by visualisation, animation, and simulation; storing and communicating design data; and processing management and control. The main strength of current CAD systems is commonly considered (Potter, 1995) to be their ability to accurately record design data[16] and communicate it to a large variety of audiences. Notice that one reason for creating representations in design—to serve as a visual aid— is not considered to be a strength of CAD.

The representation schemes used in CAD are useful in representing the data in its detailed and accurate forms. However, representing design ideas in such schemes often requires designers to input large amounts of data. Currently available CAD systems commonly offer two options for representing design ideas: representing a design idea by creating the data "from scratch" (i.e. define and represent each detail in the design thoroughly, separately, and accurately) or assembling the design by combining and modifying elements from a repertoire of "primitives" (i.e. predefined archetype elements available for use as building blocks). Most CAD systems allow modelling based on a list of primitives such as a cone, a box, or a ball, among others. The main limitation of using primitives is the limited degree of design freedom that allows minimal, and often insufficient, modifications. The use of primitives may cause another problem: I have noticed that designers who use CAD tend to prefer easily accessible shapes over shapes that take more effort to represent, even if the former shapes are less effective.[17]

Many CAD packages on the market have good capabilities in the areas of mathematical modelling, visualisation, analysis and simulation, and production. However, none provide the assistance needed in stages of creative exploration also known as "the early stages of design," when much of the knowledge is loose, vague, and ambiguous, and where creativity is needed the most.

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[16] Design-data here refers to both data describing form and data describing material characteristics. The combination of these two types of design data with a generic data on possible process, standards and configurations results in an ability to evaluate and analyse possible design processing options.

[17] It is well known in interface design (e.g. Baecker et al., 1995) that the accessibility of commands affects user behaviour.

CAD systems are commonly (e.g. Potter, 1995; Zandi, 1985) categorised into several types, according to the following characteristics:

1) The purpose of their common use (e.g. visualisation, drafting, animation, analysis, or manufacturing).

2) Their mathematical representation scheme (e.g. boundary modelling, parametric modelling, surface modelling, solid modelling, or physically based modelling).

3) The professional domain for which they were intended (e.g. CAD is the global definition encapsulating Computer Aided Electrical Design (CAED), Computer Aided Architectural Design (CAAD), Computer Aided Mechanical Design (CAMD), and CAID).

4) The phase of the process they come to support, e.g. Computer Aided Engineering (CAE), which is commonly seen as suitable for resolving stages of detailed analysis or final testing and simulation; and Computer Aided Design and Manufacturing (CADM), which facilitates the transfer of digital data into physical manufacturing systems like Computerised Numerical Controlled (CNC) cutting machines.

This categorisation is useful for labelling the system, but does not give much information as to specific characteristics.

This section described the thinking trends behind the development of existing CAD systems. However, as can be seen in the above list, CAD systems have a wide range of different characteristics. Some are developed to help a specific design phase, while others are dedicated to assisting a specific design professional practice. Let us than concentrate on CAD systems developed specifically for industrial designers. Such systems—often called CAID systems—are described in the following section.

2.2 Defining CAID Systems

CAID systems developed as part of the evolution of mainstream CAD packages, but the requirements for CAID packages tended to develop in a direction that better supports looser representations at early design stages than the connection with manufacturing and prototyping systems downstream.

An additional difficulty in designing any CAD system is the problem of specialisation versus generality. In other words, do we tailor design a system to the needs of the specific designer solving a specific problem, or do we design a more general tool to be useful in aiding designers in more generic type of situations? Using the Potter's and Zandi's definitions given in Section 2.1, a CAD/CAID tool can be specifically designed and categorised according to:

1) the designer who uses it (i.e. the designers' current work domain and design phase. For example, Chassis designer performing structural integrity evaluation of the front beam of a car in the final-detailing stages.)

2) the variety of design domains and their priorities. This requires the CAD system to fit the operations in the specific design domains being handled (e.g. dialling or depressing of various digits should be used when designing a telephone system), and

3) the required dimensions (e.g. weight or mass are best represented in dimensions such as kg. or lb.) of the problem associated with the current design domain; the CAD tool needs to have a means of dealing with these dimensions.

The above list subscribes to the common approach known as User-Centred-Design (UCD) (Baecker et al., 1995). The UCD approach argues that a (software) product is useful and usable to the user only when it was designed after the specific needs and tasks of a particular user profile.

2.3 Future of CAID Development

This project does not attempt to create a CAID development manual, but attempts to describe a fundamental direction for the development of CAID systems. The sought-after CAID tools are expected to allow, facilitate, and aid creative exploration in design by improving the way design ideas are represented in the system and the way designers interact with these representations. Such tools are expected to introduce CAID into the design-exploration stages.

As when introducing any other new tool, adding a computerised tool to the design system[18] inevitably affects the design methodologies employed. This effect is hard to predict, and once introduced, seems hard to correct; therefore, this work is seen as a first iteration on a subject that will inevitably require further development and testing of the new relationships between the designer and the CAID tools. The implications of this

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[18] Considering humans-computers as a complete design system corresponds with the adopted systems approach and is supported by ideas from ecological psychology (Vicente and Rasmussen, 1990.) The common approach to designing humans-computer systems is user-centred-design, this approach suggests designing the computerised system to fit the human user and not the other way around. (Baecker et al. 1995)

notion on a study of the human-computer and human-sketch systems are that this study should consider these systems both as a whole and as a combination of elements.

I believe that CAD's inefficiency is caused by the incorrect[19] assumption that creative design follows a comprehensive generic and systematic procedure that can be programmed into a CAD tool. I show that design in general, and industrial design in particular, follows a common pattern that is constantly adjusted and customised to fit the designer's perception of the design problem at hand. This approach classifies design as a situated practice (Allen, 1988) suggesting that there is no *generic* complete and comprehensive description that applies to all design processes. The model proposed here serves as a shell that can contain details of a specific design situation, and the detailed description appears only after the details of the design situation had been worked into this shell. This gives an opportunity to use it as a tool for planning the design process, not only for describing a design process *after* it has occurred when it is no longer useful. (A customised process applies only to the case it was designed for.)

Based on the UCD approach described at the end of the previous section, I suggest the following (partial) list should be considered before attempting to develop a CAD system:

1) What are the deficiencies of prospective[20] users? (i.e. describe the profile of the human designer)

2) What tools and procedures do designers currently use, how do these tools aid designers, and can computers replace and/or improve the practice of using these tools? (i.e. describe the tasks and procedures the above designers tend to use)

3) Where do computers excel and where do they outperform humans? (i.e. find tasks easily performed by computers that can potentially aid designers.)

The most common approach to developing CAD systems to date is the last one, as most developers try to use what they consider to be the strengths of computer systems to aid human designers. This approach—known as the system-centred-design—enforces systematic procedures, which are easier to program, on the non-systematic behaviour commonly displayed by designers in traditional design practices.

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[19] This assumption would be correct if design practice was composed of a set of well-structured procedures. This, unfortunately, is not the case for most design practices. (Goel, 1995)

[20] The relevant designers are those who are expected to use the specific CAD system. This assumes that no CAD system can possibly be optimal of *all* designers and all possible design domains.

The UCD approach described above attempts to enhance the performance of the combined human-machine system by providing computerised enhancements to existing tools and practices. UCD therefore suggests analysing existing design practices and developing a computer system that would best support these practices. UCD essentially combines all three approaches in the above list in a different and more appropriate order. Traditional design practices have evolved and improved over generations, and following the UCD approach, I believe that—as a result—these practices fit human capabilities and should serve as the basis for the design task. Introducing new CAD tools may improve the overall human-computer system, but will always be affected by the limiting factors of human capabilities as well as limiting influences of introducing computers. In other words, I suggest basing the design of CAD systems on the understanding that can be collected by observing and analysing the already mature practices of traditional design-by-sketching. I adopt the UCD approach, considering the human designer to be the central component of the human-computer system. I therefore prefer to see CAD tools reduce the load on human designers by increasing the amount of work the computer has to do, rather than by requiring designers to learn and adapt to a new practice driven by the strengths and limitations of digital-computer systems.

After recognising the importance of understanding the design task before attempting to develop a CAD system, I will now review theories describing design activities and practices as they appear in the literature.

3. Design–A Theoretical Review

The goal of this chapter is to explore sketching in design activity, and the role it plays in the design process, in order to understand how this role should be incorporated in CAID tools. The method used to explore the theories is shown in Figure 3.1.

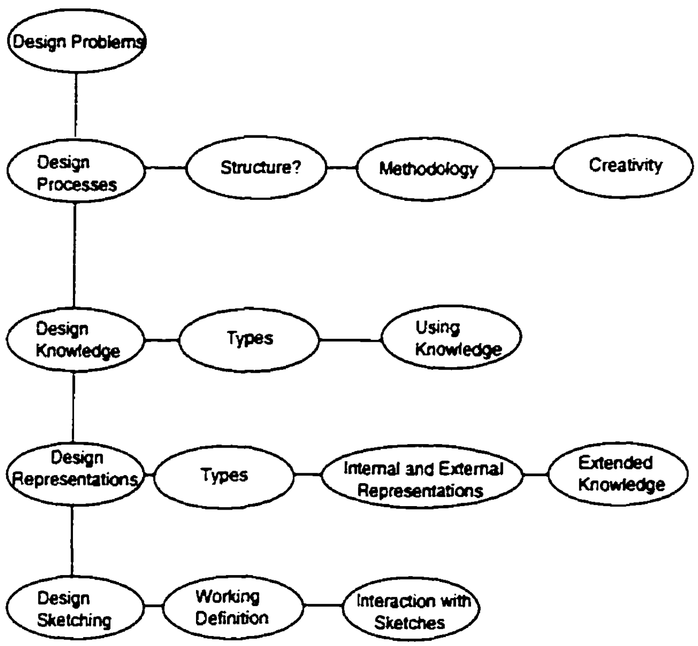

Figure 3.1: A scheme showing the structure of theoretical review

This chapter offers a review and discussion of existing theories of design by illustrating design problems in order to familiarise the reader with the subject of design, processes, and representations. The chapter starts with a description of design problems, and continues with a discussion on design processes and the activities they encapsulate. Subsequently, the subject of knowledge in design is reviewed, and then the issues of the effects design knowledge has on the methodologies used in design are explored. The chapter concludes by discussing the subject of sketches as a means of representing knowledge in design and the processes involved.

Most design professions have evolved from vernacular design, which has no prescribed methodology. Different professions within design approach design differently. Some are based on capricious artistic behaviour, while others are more methodical and systematic. This study reviews only the more systematic aspects of design practices: artistic design is not discussed here, because its practices cannot be methodically analysed.

3.1 The Nature of Design Problems

Design problems are known (e.g. Akin, 1987; Goldschmidt, 1991; Rowe, 1995, Simon, 1969) to be ill-defined rather than well-defined. They are often also wicked and open-ended problems.

Well-defined problems have an initial state, a goal, and a given set of processes and operations that may be used to get from the initial state to the goal; for example, solving a quadratic equation in algebra. In Simon's terms, these problems have an optimised solution.

Ill-defined problems do not have a clear definition of their goal state and may have more than one satisfactory goal solution. Because there are many ways of reaching a suitable solution, the cognitive operations required to solve such problems are not clearly stated and often cannot be, An example of an ill-defined problem is how can drivers turn a moving car. Herbert Simon (1969) first suggested the ill-defined nature of design problems. He added, however, that the distinction between well-defined and ill-defined problems is not clear-cut, but rather a continuum between the two.

Ill-structured problems are ill-defined problems that do not have a clear definition of a solution-procedure; therefore, they do not have a clear definition in time. One may see ill-structured problems as a temporal state of ill-defined problems. Goel (1995) reports that designers devote considerable effort (up to 30% of the time in his protocols) in constructing the problem space, which he calls *problem-structuring*. It is important to note that part of the difference between *well-structured* and *ill-structured* problems is the designers' ability to determine the above relationships between various components and aspects of the design situation.

Open-ended problems do not have a singular solution, and the search for their solution can be infinitely long (Akin, 1987).

Some design problems are so ill-defined that they are also called *wicked problems* (Rowe, 1987). Wicked problems cannot have a definitive formulation, resulting in a continuous process of formulation during their solution. The variety of possible definitions of these problems is often a result of the various domains they contain. Since wicked problems are also ill-defined; they terminate with a satisficed[21] solution, not an optimised solution. Wicked problems do not even have a termination rule that determines the completion of the process. Rowe notes that wicked problems can be considered and formulated in

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[21] The term "satisficing" was coined by Simon (1969) and refers to solving an ill-defined problem by providing a satisfactory and sufficient solution, rather than by giving the absolute optimal solution.

different ways depending on the designers' preconceptions and perception of the problem. According to Rowe, each formulation of a wicked problem yields a different direction towards solution, therefore any proposed solution can always be debated further when the problem is considered from an additional perspective.

Goel adds another notion to the discussion of representing design problems. He argues that the different design domains (or problem modules as he calls them) are intrinsically connected to the design artefact as well as to the design representation. According to his terminology, the modules of the artefact amount to "physical, spatial, temporal, and/or functional," whereas modularity in the representation is based on the information perceived by the designers, and their domain knowledge and expertise.

3.2 The Characteristics of Design Processes

The unique nature of design problems determines the nature of design processes. The different types of process types in design are defined as follows:

3.2.1 Ill-structured Processes

Processes such as design typically do not have a clear definition of the goals, situations, and the methods needed to progress from each situation towards a final state. As we can see, the term *ill-structured* is related to the term *ill-defined*: *ill-structured* processes do not have a clear definition of the *solution process* while *ill-defined* processes do not have a clear definition of the *initial state*, *end state*, or *solution procedure*. Goel (1995) goes further and suggests that design processes are *the* main case in which the distinction between ill-structured processes and well-structured ones is clear. In fact, he chooses to use the characteristics of design processes to designate the level of structure in a process, and draws a twelve-point list (Appendix A) distinguishing between design-type and non-design-type processes.

Schön (1983) and later Rowe (1987) reported that designers—dealing with ill-structured and ill-defined design problems—tend to display episodic behaviour in which they periodically reformulate the problem, considering it from different perspectives. Rowe (1987, p. 41) states that "Reformulation can take place beyond the realm of considerations within which the original [design] proposals where made, thereby opening up avenues of approach to other solutions."

This type of process may be related to multifaceted problems, where each formulation is based on perspectives that focus on different facet(s). In the example given to the participants in the observation (designing a wearable computer for auto technicians), designers must consider the different components of the device (goggles, processing unit, power supply, operating panel, etc.), as well as the different aspects associated with each of these elements (i.e. manufacturing, structure, image, usability, aesthetics, etc.). These different components, aspects, and associated perspectives in which they are considered are labelled as the different ***design domains*** of the specific design situation. Each component and aspect of the design is linked to others through the inherent structure of the problem and the different ways designers can perceive them. A change in the designers' perceived aesthetics of the product will probably result in changes in the shape of the product, the strapping requirements, the users' reach envelope, etc., which suggest that each design thread affects, and is affected by, many other threads.

This section shows the unique nature of design processes based on the different types of problems they are associated with. The following section discusses the affects of designers' physical and social environments on the way they perceive and consider the design problem and the way they express and represent possible solutions to the given design situation.

3.2.2 Design as a Situated Process

As shown in the last two sections, designers' approach and perception of the design problem may change the way it is formulated and eventually solved. Christina Allen (1988) examined the relationship between designers' work environments and their design activities. She performed a protocol-analysis conducted on graphic designers and suggests that design should be considered as a situated activity; that is, as a designer interacting with a specific physical and social environment.[22] Allen distinguishes between four aspects of design ideas:

1) *Intentions*: the abstract goals of the designer.

2) *Expressions*: ways of describing these intentions using specific media.

3) *Consolidations*: integration and combinations of expressions.

4) *Forms*: external representations used to code intentions, expressions, and consolidations.

According to Allen, these separate aspects are intertwined in a complex fashion; she suggests that the connections among aspects are often weak. She associates them with the cause for the rich and flexible design practice. The interesting part of Allen's work is the nature of the four aspects of design ideas: her theory agrees with others (e.g. Cross, Goel) who suggest that design is a goal directed activity (i.e. *Intentions*), and with those who

[22] This characteristic suggests that heuristics is less efficient in design practices which involve innovation and frequent navigation through unknown territories.

suggest that an important aspect of design activity is the creation of external representations (i.e. *Forms).* Allen makes an important distinction between *Expressions* which are connected to personal (or internal) intentions, and external representations (i.e. *Forms*). Allen's definition for *Consolidations* is similar to my definition of representation schemes, referring to the "structures" or schemes used to integrate and combine design expressions in a specific media. However, she does not describe the connection between design intentions and their associated *Forms*, except stating that they are weak and noncommittal. Chapter 5 provides a way of describing this connection by dividing intentions into separate design domains (i.e. aspects of specific design components as seen from the specific perspectives of the individual designer in a given situation) and drawing connections between them and their external representations (*Forms.*)

As we can see, design processes are complex and hard to handle. The following section discusses further the issue of formulating design processes.

3.3 Formulating the Industrial Design Process

Industrial design is commonly recognised to be a goal-directed activity (Cross, 1977; Goel, 1995; Rosenman et al., 1996; Schmitt, 1990). The most important objective is the finished product, not the process of designing it. The main reason for the absence of a detailed design process common throughout the design community is that design is a situated process; hence, it is impossible to give prescriptions for design that will be applicable to all design situations. This should not suggest, though, that design processes do not have common features and qualities that can be studied and described.

A rigid design procedure—such as an algorithm—will direct all designers starting with a given set of initial conditions toward a single design solution. This, of course, is not acceptable, because innovation is a major component of design. Thus, design processes cannot be based on a predefined or rigid procedure. It is important to note that a foundation of an algorithm is the requirement for a uniquely defined information, if a datum is ambiguous, then the of the algorithm may not lead to a definitive outcome.

Studies of design usually (Lawson, 1990) take one of the following forms:

1) *Descriptive*: the research involves describing an existing or commonly practised process in the design community.

2) *Prescriptive*: a practice preferred by the authors and mainly done for educational purposes.

Design is recognised (e.g. Lawson, 1990; Rowe, 1987) to be an ill-defined practice that cannot be reduced to a simple formula or a cookbook recipe. Thus, this project should be taken as a description of the design process and not as an attempt to give an accurate recipe for the practice of "good design."

The commonalties between different personal styles in design practice become apparent when we examine high levels of abstraction[23] where details are less prominent and general similarities are still salient; thus, analysing high levels of abstraction can uncover the strategic approaches used by the designers. Before continuing to describe the different styles and methodologies in design practice, let us review the idea of structure in design practice and the reasons for its existence.

Goel (1995) suggests that the complexity common to design problems is often handled by decomposition. He notes that a common understanding is that designers often solve design problems by decomposing them into simpler problem modules. He argues that the division process can be done in many ways and tends to depend on designers' personal domain knowledge. Goel states: "Any part of the world can be categorised in any number of ways, and any object can be related to any other in as many ways as one likes. There is no a priori way of identifying cognitively relevant boundaries and connections. However, given a specific protocol and knowledge of the domain, we can recognise modules that were relevant to the designer in that session." (p. 104). Goel notes that the resulting modules are "leaky" and that they divide the design object and the design representation are connected in a contingent manner. Goel argues that these modules are not necessarily structured in a tree-like hierarchy.[24] I refer to these design modules as design-domains since they are based on the specific domains related to the design problem at hand as perceived by the designer in the process. The notion of design domains is one of the foundations of this study. Examining these design domains allows us to analyse the design process according to the modules as perceived by designers at each given point in time and according to the way they are reflected in the external representations produced during the process.

Now, after introducing the idea of design domains, let us see other ways of analysing and describing design practice. The following two sections review other methods of describing design activity, first by showing processes as graphic diagrams and then by determining the content and the connections between steps.

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[23] The use of the term "abstraction hierarchy" in this document is based on Rasmussen (1983).

[24] Goel refers to Alexander (1965), who suggested that the example of a city—in an architectural problem—takes the form of a semi-lattice.

3.3.1 Process Maps

The two most prominent strategies in design are *bottom-up design*, where designers resolve available details of the design problem and then move forward by integrating parts into larger and larger sub-systems, and *top-down design*, where designers examine the entire problem, define details in it, and only then move to resolve them individually. Bottom-up design requires knowledge about the details of the system, a luxury which is not always given in design. The result is that the most common strategy in industrial design is top-down design. Top-down design strategy in the example shown in Figure 3.2, uses the most common method of describing the steps taken and the direction of flow between them. This method is based on diagrams called Operational Sequence Diagrams (OSD).

Let us add more detail to our description by stepping one level down in abstraction. In his theory of abstraction, Rasmussen (1983, Rasmussen et al.,1994) suggests that reducing abstraction results in a reduction in aggregation and an increase in detail; what can be added to the picture we have of design strategy in order to make it more useful? We know the general direction the strategy takes, but we do not know the steps taken in that direction. Most theories describing the design process tend to generalise it, so that the theory applies to more diverse cases, but giving a complete description of the process while still giving sufficient detail is difficult. Hence, descriptions must pursue one of the following methods:

1) Describe only aggregated and abstract operations (e.g. design, visualise, model, simulate), which are left as basic and unexplained elements of the diagram.

2) Describe large numbers of detailed operations (e.g. move x to point y, copy, etc.) This approach can result in a complex and hard-to-follow map.

These two approaches to describing design processes differ greatly. OSDs do not reflect quantitative progression of time in the process; they depict the time only by showing progress between described steps. The operations are depicted as blocks connected by arrows. The blocks represent steps and the arrows depict the direction of progress. Another type of OSD that is often used describes the steps and the progress, and also

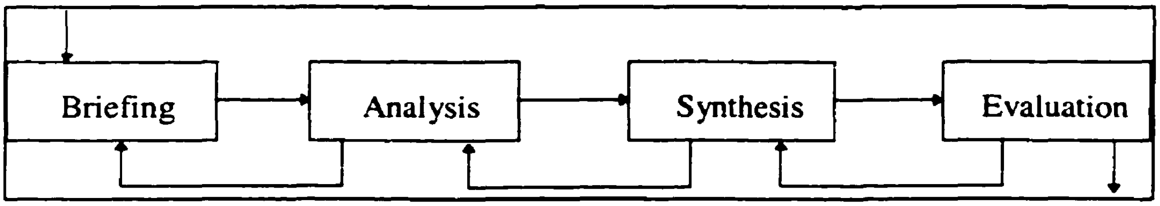

Figure 3.2: An operational sequence diagram (OSD). The diagram depicts the four step model proposed by the Royal Institute of British Architects (Lawson, 1990).

depicts the objects transferred between the various steps of the process. The common form of describing the design process in design research literature (Lawson, 1990; Rowe, 1995) is by using flow-charts that serve as OSDs, such as the example seen in Figure 3.2.

These maps are not customised for individual designers in a specific situation; rather they describe an archetype with features common to a range of design processes. The most detailed of these maps show specific actions, as well as the flow of action going from one step to another. There is, however, no detail about the elements transferred between these operational blocks (e.g. design sketches, design models, etc.).

Lawson (1990) gives these maps to describe structures of design process, which are divided based on functions performed in certain time stages. The following process scheme was adapted by Lawson (1990, p. 24) from the Royal Institute of British Architects (RIBA) practice and management handbook. The process map (shown in Figure 3.2) divides the entire process into the following stages:

1) *Assimilation*: The accumulation and ordering of general information and information specifically related to the problem in hand.

2) *General study*: The investigation of the nature of the problem, including exploration of possible solutions and means for finding a solution.

3) *Development*: The development and refinement of one or more of the tentative solutions isolated during stage two.

4) *Communication*: The communication of one or more solutions to people inside or outside the design team.

Even Lawson agrees that this is an over-simplified map of the design process and does

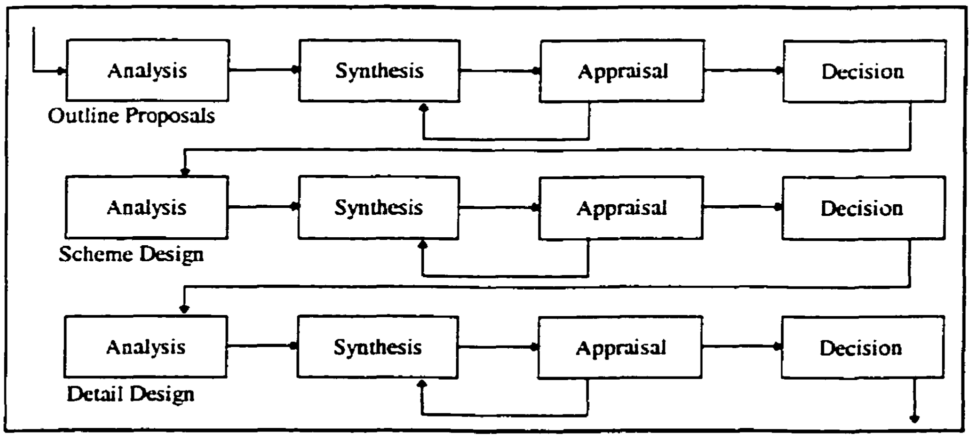

Figure 3.3: A more detailed diagram describing top-down strategy in the design process (Lawson, 1990, p. 26)

not really add any understanding to the problem at hand. This is an example of an OSD with little detail and with rather large stages (or blocks), each being huge and complicated to understand.

The OSD in Figure 3.3 shows a repetitive cycle in the design process. This diagram might raise suspicions that a solution to the problem of representing the design process lies in providing a description in greater detail. This, however, is proved incorrect by observing the more detailed map in Lawson's monograph (1990, p. 26) shown as Figure 3.3. Clearly, adding detail does not solve the problem of understanding the process for, in a more detailed map, some levels of representation are removed, which requires audiences to rely on their working memory (Wickens, 1992) and can be harmful to the creation of mental models and to the understanding of the design process.

Describing the process by using an OSD gives some detail about the steps in the process, but it is not complete. For example, design processes often involve iterative progressions, depicted as loops in the diagram, but no information is given about differences between the given iterations. Such a description can pose a limitation on researchers interested in analysing contribution from each iteration. When designing a CAD system, we need to understand the requirements from the computerised model at every stage of the process, and such an understanding cannot be gained from OSDs.

If we understand that more detail is not always helpful, we should try to comprehend why this occurs, and review the way we learn about the world and the way we memorise our understanding. An incomplete description of human understanding is available from several psychological theories, but such theoretical issues are beyond the scope of this project. One psychological theory, however, needs to be mentioned because it serves as the basis for several design theories, such as Akin's theory of design knowledge and Goldschmidt's dialectics of sketching to name a few.

Gestalt psychology (Kanisza, 1979) describes human psychological processes as based on the organisation in the processed information. The *Gestalten* or Gestalt concept (German for "good form") suggests that human thinking, especially human visual perception, best deals with whole-elements that represent the elements in the best-form. In relation to the design process, Gestalt psychology suggests that it is easier for us to understand a situation, diagram, or problem if it is arranged in a way that helps us divide it into chunks. This arrangement as more abstract aggregated-items reduces our need to remember separate details, and allows us to remember each datum by the chunk it belongs to and then understand the relationships between chunks.

Goldschmidt defines "seeing-as" in her dialectics of sketching by referring to designers' tendency to *see* (and describe verbally) objects *as* based on a specific meaning of the object. For example, a room is seen (considered) as a hallway.

Akin sorts design knowledge (see Table 3.1 on page 38) according to its generality. He too bases his theory on a Gestalt concept—Schemata, which refers to the abstract pattern governing the items or objects.

Design behaviour includes a combination of physical (motor) and cerebral activities; it is difficult to separate these two types of activities. The following section discusses structure in design processes without separation between the two activity types.

3.3.2 Determining Structure in Design Processes

As mentioned in the beginning of this chapter, the purpose here is to understand the structure in design activity and describe it from two perspectives: from a general theoretical perspective by examining common patterns in general design behaviour; and from a detailed perspective, often through applied studies of empirical nature, by focusing on common patterns in detailed design operations.

Schön (1984) describes design from a highly abstract and theoretical level. He gives an interesting metaphor for the design process; he refers to it as a *web of operations* where "the web of moves has many branching" (p. 99). This correlates with the vertical structure[25] of the design process suggested above. Schön notes that the level of designers' expertise can be measured by their ability to efficiently navigate through this web. The web metaphor not only points out the complexity of the process, but it also provides us with a way of finding our way around it. Schön describes the design problem as a composite of design domains that contain the understanding of the partial solutions to the entire design problem. He suggests that a solution is possible for expert designers, but does not provide us with a method[26] for analysing this ability.

Schön postulates that the web of design moves is related to the different aspects of the design problem at hand, including the problem domains. The domains correlate with the problem disciplines; however, a discipline can be broken later into less abstract and more detailed problem domains.

As in the case of OSDs, a different approach to describing the design process is selecting only a small portion of the design activity (i.e. a design operation) and describing it in greater detail. This type of description is common to empirical studies of the process that

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[25] This way of describing the design process by means of vertical and horizontal axes refers to the depth and breadth of the design problem space respectively.

[26] Schön suggests that science is limited in dealing with problems such as design, which are solved by reflection and not by scientific rigor.

include large amounts of data gathered from observing actual design practice (e.g. Goldschmidt, 1991, 1992, 1996; Suwa and Tversky, 1996). This approach is more powerful in describing actual cases, but encounters great difficulties in describing larger portions of the process. This difficulty can be attributed to the difficulty in parsing the recorded operations into higher level chunks and perceiving the interactions among this level of operations being used. Gabriela Goldschmidt proposes an example of a theory emerging from empirical results.

The 2D Linkograph (Figure 3.4)—a method of performing this analysis was suggested by Goldschmidt (1989)—depicts each design move as a point on the time axis and each link between two connected moves as diagonal lines from one to the other. Each chunked cluster is then visible as a cluster of diagonal lines in a certain area. The problem with these diagrams is that they only show that a discontinuity exists, but do not describe the nature of the jumps between chunks. The data is collected by means of thinking aloud (Goldschmidt, 1996). This graph is useful for depicting connected chucks in the design process, although it does not allow us to follow the transitional *jumps* between these chunks. The advantage of Linkograph is its simplicity, which allows us to use it on any protocol without much preparation or analysis.

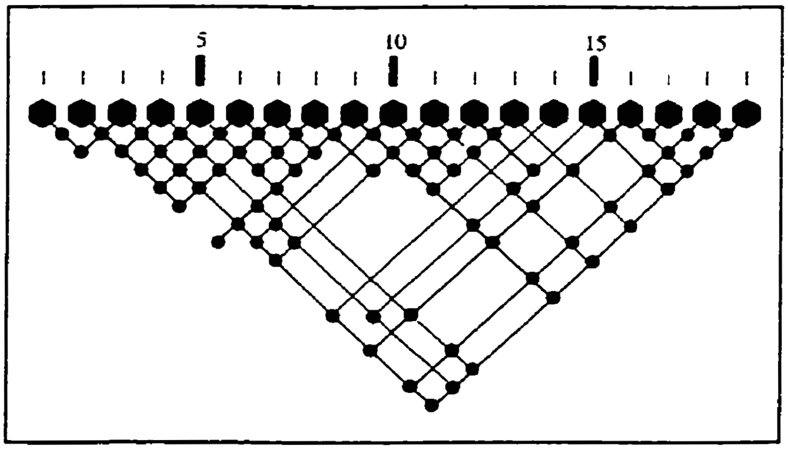

Figure 3.4: Goldschmidt's Linkograph, this example depicting the protocol of the Delft workshop.

Schön's theory is more of a generic description of professional practice, while Goldschmidt's theory serves as a tool for determining structure in design activities. Both theories are concerned with creative practices in design, which the following section explores in further detail.

3.4 Behaviour and Methodology in Design Processes

As described in the previous section, common design behaviour can be described at various levels of detail. Descriptions of detailed design operations shows common design operations, whereas less detailed and more abstract descriptions of common design behaviour tend to focus more on the strategic methodology common among the design community. This section describes several common methodologies and strategic approaches in design.

Design has always existed as a vernacular activity; people have devised objects and products throughout the evolution of human history. The process of designing has been considered to be a mysterious and a God-given talent. Design has evolved to become a profession only during the current century. Today's design professionals range from design-engineers who use more systematic procedures, to artistic-designers who practice design as applied art. A recent study (Fisher, 1995) reports that the number of artistic-designers is decreasing rapidly and, in Europe, they are found mostly in the design education institutions. The mystery surrounding design practice is a result of the unique nature of the design problem (i.e. an ill-defined, open-ended, and usually wicked problem) and from the inability to understand design practice by simple observations. Design practices are hard to analyse because much of the process is invisible (it is performed internally as a cognitive process) and even visible outcomes are often coded so that they can be understood only by the designer who generated them and, most often, are illegible to non-designers (Goel, 1995).

Design activity ranges from the artistic and capricious type to the more structured engineering types; thus, discussions of the different types of design behaviour requires different presuppositions and ways of analysis. The review in the following sections starts with scientific (a more structured and analytic approach) to less structured and more intuitive approaches, such as design heuristics and design as a process of reflection-in-action.

3.4.1 Scientific Search and Design

The most organised approach to design—often applied to more scientific design domains such as engineering—was originally developed by Herbert Simon (1969). According to Simon(1981), "...the task of science disciplines [is] to teach about natural things: how they are and how they work. The task of engineering schools [is] to teach about artificial things: how to make artefacts that have desired properties and how to design" (p. 129). He suggests that science is concerned with how things are and how they work, whereas design is concerned with "how things ought to be" (p. 133).

Simon describes the logic behind design practices using terminology from statistical decision methods. He suggests that the design problem is to optimise the connection between the "inner-environment" and "outer-environment" using a "utility-function" under the given constraints. The *inner-environment* is the details concerning the environment within the design solution, and is usually given in command variables. The *outer-environment* is described as the facts and probable notions that are expected to exist regardless of the design situation, such as the laws governing nature or human behaviour. He defines *utility-function* as the goals of adapting between the command variables and the environmental parameters. Simon defines design as an optimisation problem as: "to find an admissible set of values of the command variables, compatible with the constraints, that maximise the utility function for the given values of the environmental parameters" (1981, p. 135). Simply stated, constraints characterise the inner-environment, while parameters characterise the outer-environment; the design problem is to find the variables that maximise the given goals under the given constraints.

Also, Simon notes that design problems have huge or even infinite number of possible solutions, especially when dealing with an open-ended problem, suggesting that using a rigorous search for the absolute best solution is unrealistic at most. Therefore, Simon suggests that design be based on finding the satisfactory and sufficient (which he calls "satisficed") solutions rather than the absolute one. He calls this process "satisficing solutions" and defines it as finding satisfactory and sufficient solutions using a moderate search based on comparing the merits of different possible solutions. The problem of using this type of search is that it involves predictions of the prospects of possible design directions.

Simon suggests the following guidelines for satisficing solutions:

1) It is better to use multiple design directions simultaneously and discard directions when they seem less valuable.

2) There is a need to continuously evaluate designs in order to navigate through the range of possible solutions and to decide on termination of the process.

3) It is useful to decompose the system into sub-systems that are more easily digestible.

Many industrial designers find Simon's approach too rigid and confining. When it comes to rigid constraints, they often prefer the use of "rules of thumb" or heuristics.

3.4.2 Design Heuristics[27]

Designers often need to evaluate or simulate design situations. Instead of using accurate search and evaluation methods, they 42use rules of thumb. The following section reviews such a methodology suggested by Akin (1987).

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[27] Heuristics are rules of thumb that improve the problem-solver's efficiency in finding solutions by identifying "promising" alternatives and eliminating those less likely to yield solutions (Feigembaum and Feldman, 1963 cited in Akin, 1986, p. 36).

Ömer Akin examines the design process through the perspective of information processing theory and suggests that design practice is based on heuristics. He argues that heuristics is useful for designers because it is powerful in solving the ill-defined problems so common in design. He concludes that computers could assist design processes when two basic elements are understood:

1) The design knowledge base composed of problem-solving, physical intuition, and inductive reasoning (p. 168).

2) The rule base used for evaluating the design situation.

Akin recognises that designers commonly employ intuition in their practice, and suggests that it should be seen as part of the design knowledge and that design is actually based on two parallel hierarchies: constraint hierarchy, which helps designers prioritise the application of goals and constraints in their process; and decomposition hierarchy, which helps designers reduce the complexity of design problems.

Akin points out an essential difference between well-defined and ill-defined problems. In well-defined problems, all possible types of representations and transformations in the problem can be known a priori, whereas in an ill-defined problem, only the initial state is known. He argues that this initial state is commonly given in the form of a design brief; however, even the best brief cannot express the initial state completely and comprehensively, because some knowledge about the problem (or the initial state) can only be understood using what Akin calls "natural extensions" (1986, p. 21), which include a lifetime of human experiences, documents, etc., that cannot be expressed in a design brief. Akin also postulates that in handling design problems, we have to figure out the "rules" of solving the problem. These rules are often not available or even anticipated during initial stages of the design work, requiring designers to perform in a state of uncertainty and act based on intuition, and learning the rules as they proceed in solving the design problem.[28] It is recognised (Simon, 1969; Akin, 1986) that the ill-defined nature of design problems makes designers solve these problems by "satisficing" rather than by "optimising."[29]

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[28] This notion is shared by Lawson (1990), who found out that designers solve problems by learning the rules that govern the problem as they proceed in the solution process, as opposed to scientists and engineers who usually start solving the problem only after they have completely figured out its rules.

[29] When a well-defined problem is given, reviewing, evaluating, approving, or rejecting all possible solutions can yield the (optimal) solution; this is defined by Simon as optimising solutions. In the context of ill-defined problems that are often also open-ended, it is impossible to search exhaustively through all possible solutions. In cases of ill-defined and

Although the concept of hierarchies in design knowledge suggested by Akin seems correct, it is better described separately in the terms of functional (means-end) and component (part-whole) decomposition hierarchies, as defined by Jens Rasmussen (1994.) Rasmussen et al. suggest this because they consider design to be a goal-directed activity. Rasmussen et al. propose a concept they call Abstraction-hierarchy, this concept analyses well-defined, well-structured systems and their related cognitive processes, by decomposing the system using functional (means-end) and aggregation (whole-part) relationships.

According to Akin (1986), heuristics include all possible methods, procedures, and principles that help satisfice the problem or help reduce the search for satisfactory solutions. Rowe (1987) suggests that heuristics are usually indicated by actions rather than associated with contemplation, and suggests that a certain type of heuristics is useful in order to increase the sense of familiarity in open-ended situations. According to Klein and Crandell (1995), this familiarity with situations commonly determines the plan of action of experts in time-constrained situations. The concept of heuristics is closely related to the organisation of the relevant knowledge and the format used to represent this knowledge.

Akin develops a series of fifteen heuristics (i.e. "rules of thumb") that he believes should direct design practices (Appendix B). He suggests that any computerised tool developed to assist designers by automating the design process should incorporate these rules in its processing logic. Akin's list of heuristics is limited in efficiency. First, because like any other type of heuristics, it is meant to cover a large variety of cases, and as such, ends up being too general to completely, and without enough detail, solve every specific problem. Second, because when dealing with a complex problems, heuristics requires users to apply a large number of points that are often too large to remember and thus less effective. For example, Akin suggests to deal with "more constrained first." This rule is not easily applied without a useful metric to quantify constrains of different suggestions; a more detailed guideline is required in many cases. Design heuristics are mainly useful when they come in small numbers; when their number increases, they become harder to remember and use.

According to Rowe (1987, p.75) heuristics are based on reducing the necessary knowledge into a set of simple rules. Rowe (1987, following Schön, 1983) resolves this

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open-ended problems, only a satisfactory-sufficient solution is sought. Heuristic search is a common method of satisficing problems. In heuristic searches, designers utilise a set of heuristics or thumb-rules to evaluate the prospects of a candidate solution without evaluating it thoroughly. This allows designers to quickly eliminate less promising design-directions and hopefully converge on an avenue leading to a promising design solution.

limitation by asserting that designers employ different sets of design heuristics and different mental-models during different design episodes. This contradicts Akin's claim for developing *the* design heuristics applicable for *all* design situations.

According to Rowe, simple rules can be used only when the knowledge about problem A is sufficient and the situation is not ambiguous. When the design problem is more complex and ambiguous, designers must employ additional abilities, techniques, and intuitions. The next section describes this type of methodology.

3.4.3 Reflection-in-action in Design

In more subtle and rich situations, designers often resort to their professional artistry Donald Schön (1984) describes this type of methodology and practice in professional design activity to be exemplary to other fields. This project considers design behaviour to be a type of "reflection-in-action" as described by Schön (1984).

Schön suggests that aside from information and procedures that can be formally taught, professional practice also includes a component based on a familiarity with the professional field. He argues, for example, that a brilliant lawyer is not necessarily one who knows all the law textbooks, but rather one who has developed an understanding of how to practice law, including how to speak in court, how to present his case to the authorities, and how to resolve complex problems based on previous experience. Schön also suggests that professional ability is composed of two aspects: the *knowing-in-action* and the *reflection-in-action*, where knowing-in-action describes the knowledge of how to do things that are performed with little attention and effort, and reflection-in-action is the ability to process unique and novel situations that cannot be processed by knowing-in-action. This approach suggests that design, like other behaviours involving highly complex tasks, demands the practitioner perform tasks without always being able to completely analyse the situation and the outcomes resulting from possible actions. In such cases, practitioners use their professional understanding and their ability to interact with abstractions of the situation to help them navigate through the situation. Schön defines this type of spontaneous practice as "knowing-in-action." He suggests that it often results in unexpected outcomes and is paramount to creative practices in design.

Schön suggests that design is a profession that best demonstrates reflection-in-action. In fact, he defines reflection-in-action by describing the professional abilities and practices of designers. An important characteristic in Schön's theory of professional practice is that actions and procedures in reflective professions cannot be described in a matter understood by audiences outside of the profession. For example, when a design teacher in Schön's book helps a student design, the teacher uses terms and actions that seem unclear to the student at first, and can only be perceived after trying these actions repeatedly until they are performed without assistance. The design teacher acts only as a coach.

Now that two generic methodologies (not specifically unique to design practice) have been examined, we can focus our attention on a methodology with characteristics unique to design.

3.4.4 Episodic Nature of Design Processes

It was mentioned previously that design problems are multifaceted and complex, and that this affects the design methodologies used to solve them. This section reviews the references to this phenomenon found in literature. Further details of the structure of design processes are given in Chapter 5.

Peter Rowe suggests that earlier stages of design processes often display an episodic characteristic. Designers seem to "jump" between different aspects of, or areas of concern about, the problem at hand, but Rowe does not describe what these problem aspects are or how designers create them. Instead, he reports that "the results of these separate investigations usually cohere into a more singular direction for the design activity, although not necessarily as a linear progression of reasoning" (1987, p. 34). Rowe's analysis of his observations did not explain how, why, or when a transition between episodes occurs either. According to Rowe, these episodes have interior logic inherent to the design situation and to the organisational procedures used in the process; this episodic nature of design processes ranges from well-defined to nebulous. This interior logic is not described in detail, but the different episodes seem to correlate with the different design domains, as they construct the design problem in much the same way. The analysis of design protocols in Chapter 4 is based on examination of the relationships between the design procedures and the focus of designers' attention at a given time. This analysis is based on Rowe's suggestion that the progression in the design process becomes apparent this way even though not necessarily linearly.

Rowe reports that the process is composed of "moments of blinding," where designers do not recognise obvious relationships between various considerations, and periods of backtracking. His conclusion suggests that these characteristics are related to the way designers represent their design ideas. According to Rowe, the episodic structure of design activity commonly displays the following characteristics:

1) Designers move "to and fro" between areas of concern in the design situation.

2) Some of these episodes involve free speculation, whereas others are more sober and rigorous.

3) Each episode involves a specific orientation of dealing with the design.

4) The episodic nature is less pronounced when the design situation becomes more determined and defined.

According to Rowe (1987), transitions between episodes are related to either the inherent structure of the design procedure being employed or to the interior structure of the subject matter (i.e. the particular design situation), where the structure of the design procedure is a combination of designers' personal design styles and their perception of the design situation. To summarise, Rowe's approach suggests that episodes in design behaviour are related to the design situation and its perception by the designer, and are affected by the representations used by the designer.

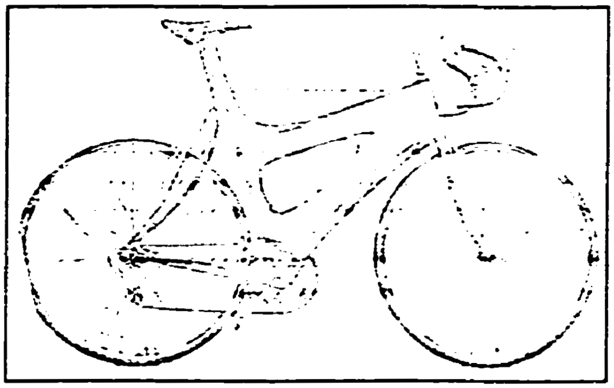

Figure 3.5: The design sketch leading to the new design. The new concept was originally drawn over the existing design and not superimposed at a later stage. (Edmonds 1994)

The past section described different approaches to design, ranging from more structured scientific search methods suggested by Simon (or approaches which try to express some artistic behaviour in quasi-regulated form, such as the rules of thumb suggested by Akin) to less structured ones suggested by Schön, which rely on professional artistry. Episodic behaviour, as reported by Rowe, is an example of a characteristic of design behaviour that relates to professional artistry. All these approaches rely on professional and background knowledge for their successful application. The following section describes the intricacies of such knowledge in the design field.

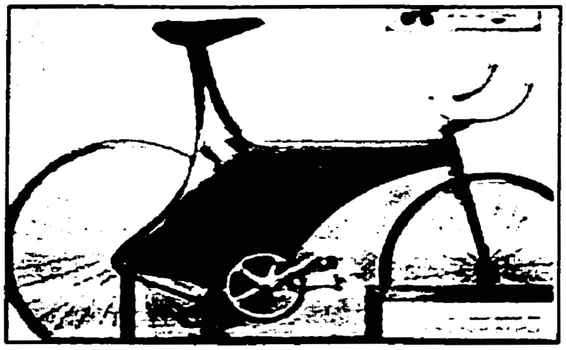

Figure 3.6: The final Monocoque bicycle (Edmonds, 1994)

3.4.5 Creativity in the Design Process

The focus of this project is the creative processes in design and ways to support them. Thus, after becoming familiar with the base theories, we can proceed to explore connections between creativity and patterns in design behaviour.

It is recognised in the literature that new concepts and ideas involve a jump or quantum leap that cannot be anticipated; the historic cases of the discoveries of the DNA and the theory of special relativity are discussed in Lawson (1990). This leads me to believe that these jumps are important to the analysis of the design process, since they reflect, more than anything else, the creative instances in design. Chapter 4 demonstrates the correlation between these jumps and the emergence of new concepts and ideas, in an empirical design observation conducted for this study.

The importance of emergence (discussed in Chapter 2) as a phenomenon in design is obvious and cannot be overstated, although studies on this subject have yet to produce an all-encompassing theory that can exactly explain what is the creation of a new concept and when precisely such an idea emerges. Ernest Edmonds (1994) conducted an interesting study on emergence by examining records of Mike Borrows, the creator of an innovative racing bicycle frame. In this case study, the bicycle design started with a regular diamond tube frame that was stretched to the limit of its structural envelope. The emergence of the new concept is salient in the produced sketches, one of which is shown in Figure 3.5. At that stage, the designer "arrived at a radical transformation of the concept of the bicycle frame" called the *Monocoque*, shown in Figure 3.6.

This innovative frame is constructed from plastic resin and no longer based on connected tubes. The new idea emerged as the designer starts with the common approach and then sketches a new form *over* a drawing of a "common" frame. Once the shape exists, a new structural mechanism is used, and the new design can be completed.

Here, the designer focuses on the shape that evolves as a result of "deforming" an existing bicycle steel-pipe frame in order to improve riding performance. Then he "jumps" to focusing on the manufacturing technique and its related mechanics-properties of the plastic-resin. The "jump" between the two problem-domains (geometric shape for improved performance vs. material properties) is immediately followed by development and recognition that the frame can be *reformed* to yield better results under the changed set of constraints. This concept of "jumps" between different design perspectives or problem-domains will be expanded and examined in Chapter 4.

Sections 3.4.2 and 3.4.3 describe the possible advantages and limitations of using heuristics in design. The example given in this section demonstrates a designer disregarding the known "rules" of designing bicycle frames and, as a result, achieving a superior solution. Rowe and Schön agree that designers often rely on reflection-in-action, professional artistry, and intuition to overcome the difficulties that arise from ambiguity and lack of specific knowledge. They suggest that, as shown in the above example, designers tend to switch between different sets of heuristics as needed for the given design situation.

This poses two questions:

1) How are the above-described patterns, procedures and methodologies that govern design behaviour related to design knowledge?

2) Is the specific procedure of sketching over existing drawings common among other designers and, if so, why is it useful?

The first question is answered in the following section, and the second is answered in Chapter 4 in the course of discussing *oversketching*.

3.5 Knowledge in Design

It is agreed (Akin,1987; Schön, 1983, 1987; Rowe, 1987) that design behaviour is based on the application and use of professional knowledge and expertise, but what is that knowledge and how is it used in design? The following section tries to shed some light on the matter.

Schön (1987) examines design from a pedagogical perspective and suggests that professional knowledge in general, and design knowledge especially, can be divided into two types: knowledge that can be formally taught, and knowledge that must be gained through practice with help from coaching. He argues that design is probably the best example of such professional knowledge.

Akin examines design from a pragmatic perspective. He tries to find the rules that govern design as a unique problem-solving process and divides design knowledge into six types, as shown in Table 3.1.

Akin classifies knowledge items as *things*, *relationships*, or *procedures*. Things and relationships are both classified as related to declarations, whereas procedures are their own class. General knowledge includes archetypes and rules of categorisation and practice, while specific knowledge depends on the situation.

Table 3.1: Design knowledge according to type (Akin, 1987, p. 34)

	Specific	**General**
Declarative (things)	tokens	schemata
Declarative (relationships)	attributes	rules of inference
Procedural	transformations	heuristics

Tokens include both distinct entities and normative references to classes of entities. For example, *Barcelona chair* describes a specific object.

Schemata specifies "a chair" that is generic and refers to a device that facilitates seating.

Attributes are descriptions of specific objects and relationships.

Rules of inference include knowledge about general cases.

Processes and procedures are related to either generic or specific situations. As shown in Table 3.1, *heuristics* are general procedures, which could be applied to specific situations resulting in specific *transformations.*

Akin's definitions of procedural knowledge seem inconsistent: initially, it is defined as the knowledge of "how to." However, it seems that Akin makes a hidden assumption in Table 3.1, suggesting that it is always possible to represent design know-how either as a transformation or as a heuristic rule. His assumption seems odd to me, as even the example of "how to ride a bicycle" given in Akin's definition is impossible to represent.[30] Other tasks that are impossible to represent may involve kinaesthetic knowledge (e.g. riding a bicycle), cerebral knowledge (e.g. practising medicine), or a combination thereof. The characteristic of such tasks is that the participant who performs them often cannot describe his or her actions. The difficulty in describing actions was discussed by several researchers (e.g. Ericsson and Simon, 1987; Klein and Crandell, 1995). the following reasons are some causes of this difficulty:

1) The difficulties in reporting the operations, either when trying to report simultaneously with performing the task in itself, or remembering necessary details when reporting after task completion.

2) The limitations of describing complex tasks in a manner understood by the audience.

3) The limitations imposed by the representation scheme used to describe the action, including the audience requirements. For example, verbal testimonies are limited in their ability to describe forms, whereas visual languages, such as mechanical drafting, require learning of background information. Schön argues that, in many cases, "know-how" is impossible to represent.

Akin shows that design knowledge is organised hierarchically by describing design processes as composed of a series of simpler tasks, each of which can be followed by several options. He suggests that design knowledge is what helps the designer choose one of these options. According to this description, task T may be followed by one of (t1, t2, t3... tn) and t1 may be followed by either (t11, t12...t1n) etc., as shown in Figure 3.7.

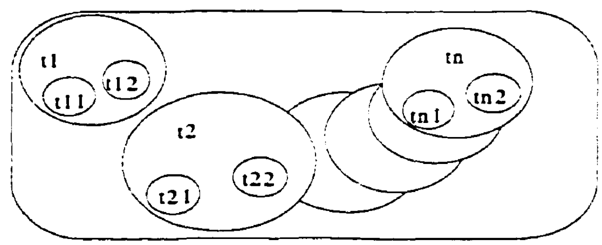

Figure 3.7: The hierarchical structure in design knowledge, as proposed by Akin (1987, p. 37)

This suggests that it is possible to represent design knowledge hierarchically according to a mean-end analysis. However he also suggests that design is actually based on two

[30] I argue that it is impossible to teach someone how to ride a bicycle without them actually trying to acquire the skill themselves. An explanation can be given, but even then, it is still a process of self-teaching through trial and error, and discovery.

different hierarchies: constraint hierarchy and decomposition hierarchy, this structural duality suggests that when the problem is not well-defined, then its related knowledge may not always be completely structured hierarchically.

Rassmusen et al. developed this approach further and suggests that when applied to well-structured problems, this yields what he defines as *abstraction-hierarchy*. The concept of abstraction-hierarchy is a five level hierarchy based on means-end analysis and part-whole decomposition. The top level of abstraction is related to the goals and constraints of the system (i.e. why have the system?). This level is then decomposed into the strategies (what can/should done to achieve the goals under the constraints?), the system's functionality (how can the above be achieved?), activities and processes, and finally the physical form and material configuration of the systems' components.

According to Rasmussen, abstraction-hierarchy is useful because it provides a tool for systematically solving complex yet well-defined and well-structured problems.

Rasmussen (et al.,1994) describe several design activities and show that designers often switch among different problem-domains during the design process. He states (following Alexander 1964 and others) that the design process cannot be described as a well-organised sequence of events as seen from a single perspective; where a perspective is based on a particular way of formulating design situations from problem-definition to a specification of a final design solution. Rasmussen concludes that design situations typically correspond to open-ended and ill-defined problems involving multiple perspectives, where the total knowledge needed to resolve these situations is usually distributed among several professions or problem domains.

Rasmussen suggests that in cases involving complex, open-ended, and ill-defined problems, using a tree-structure may help problem-solvers (i.e. designers) represent and communicate intentional information, as well as help in navigation and co-ordination activities among the different domains. The biggest difficulty is to understand and construct the appropriate tree-structure for all the necessary knowledge. Chapter 5 describes an attempt to visualise this structure based on the different problem-domains and design perspectives involved in a particular design activity.

Goel (1995) suggests that the connection between the input (i.e. the information about intended users and the use of the product) and the output of the design process (the representation of the designed artefact and finally the manufactured product) is based on abstraction-hierarchy.[31] It is important that Goel believes that design knowledge,

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[31] It is not clear whether Goel and Rassmusen refer to the exact same term because they do not refer to each other's work. However, Rasmussen's theory seems to be a complete one, whereas Goel seems to use the term without such backing theory.

representations, and practice are not modular and orthogonal (i.e. some connections exist between the various "leaky" modules). He calls this type of modularity "near modularity".

Design knowledge is quite diverse and includes knowledge of facts, figures, procedures, and operations. Procedural and operational knowledge often cannot be expressed in any other way except performing the task. This type of knowledge is hard to teach, because it is often based on self-experience and often is subject to influences of personal style.

The next section describes the way designers use these various types of knowledge in their practice.

3.5.1 Using Knowledge in Design

Now that we are familiar with some theories regarding the unique characteristics of knowledge in design, we can see how designers use knowledge in their professional practice.

Processes involving knowledge are cognitive processes. A common[32] paradigm for describing cognitive processes in general, and design thought in particular, has been the theory of human information processing by Simon and Newell, published in 1972. This theory looks at the human mind as a component of a bigger information processing system from where it gets information, computes results, and communicates the results back to the rest of the system's components; in effect, reducing human thought to machine-level operations. A newer theory for describing higher level human mind functions, published by Schön in 1983, deals with human thoughts as artistic reflections over design and other social situations. Schön's theory is clearly more appropriate for describing design, because is better describes the artistry governing design behaviour.

The problem in describing the cognitive processes in the design process can be associated with the non-orthodox[33] approach designers take to their work, which suggests that designers employ a unique logic to guide them in their design practice. Lawson (1990) reports on an experiment he conducted in 1977 that demonstrated that designers operate differently than scientists (i.e. people with extensive science background) and discovered that designers generally do not plan their process "by the book," but follow their "gut

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[32] All the sources reviewed in this chapter (Akin, Goel, Goldschmidt, etc.) refer to Simon and Newel's work as their initial foundation.

[33] Non-orthodox here refers to the tendency, reported by Lawson (1990), of designers to search for a solution while familiarising themselves with the rules and information required to perform that search.

instincts" and intuitions arising from the situations they encounter, based on their past experiences. Designers are also considered to be visual thinkers who require sketching, which is quick and easy to use after the basic skills and techniques are mastered, as a means for visual calculation and experimentation. Sketching is, therefore, the most effective (Hennessey, 1994) design tool available for designers and engineers.

The designer acquires information from external and internal sources, such as pictures, plans, drawings, and memory; the process of acquisition is based on perception of these sources. Akin suggests that designers associate outcomes (including cost and benefit) to given information. He reports that designers use this mechanism to evaluate possible design moves and navigate through the design problem space, and *project* or anticipate their outcomes. This concept of information perception is related to the concept of *affordances* in *Ecological Psychology* (Gibson, 1966), which suggests that a design solution (and its environmental setting) affords its probable behaviour.

Designers' ability to read affordances is allowing them to operate in the environment based on their lifetime experience, training, and inductive logic. Rasmussen explains that affordances are the constant behaviour of objects that can, once learned, give indication of the object's future possible response to a given action. For example, a button *affords* that it will invoke or activate some action when it is pressed. Affordances are common in both natural and artificial environments. Rasmussen draws a connection between affordances and the mental models they invoke. He suggests that affordances contribute to the creation and use of mental models by providing specific details about the invariant behaviour of individual objects in the environment. This is important to our discussion of design knowledge, because designers, according to Rasmussen, tend to use various mental models during various stages of the design process.

According to Rowe (1987 following Schön 1983) designers evaluate and anticipate the possible outcome different design avenues at various times during the design process in order to choose the most promising avenues and abandoning the rest. They further argue that designers often base their evaluation on different sets of heuristics depending on the perspective they use to view the design situation at that time.

To summarise, designers tend to display episodic patterns in their design behaviour. During each of these episodes, they interact with the necessary design knowledge by focusing on a specific part of the problem, usually considering it from a particular perspective, and thus using a particular appropriate mental-model. Milton Tan argues (1997) that a pivotal problem in developing and using CAD systems is the ability to construct a system that would facilitate the necessary transformations and conceptualisation of design knowledge. In other words, a system that can "read" the right meaning(s) in a design representation and allow the designer to easily and effectively transform it to create new ideas. Tan argues that this crucial for creating better CAD systems. He also notes that achieving this goal requires further understanding of design representations, knowledge and activity. The following section examines the subject of knowledge representation in design a little further.

3.6 Representation of Knowledge in Design

In the last sections, we saw what types of knowledge exist in design and how they are used. Now let us consider if and how they could be represented, and how their representation affects design.

Akin analyses the different methods of representing information in design from an information-processing perspective. In doing so, he tends to generalise and reduce cases into archetypes.

Newel and Simon (1972) give a related concept in their discussion of the knowledge found in representations. They suggest that some information can only be extracted through "additional processing": a concept they call the *Extended Knowledge State*, which is knowledge that includes the information, which is not immediately accessible by the reader. Incongruity, ambiguity, and implicit meaningfulness describe some characteristics of extended knowledge.

The problem with representing this extended knowledge is that it inherently cannot be directly represented, i.e. when the information is accurately represented such as in existing computerised representations, it becomes a part of the directly represented information and is no longer extended knowledge. In many cases, extended knowledge is put in a representation intentionally (Tang, 1989), but in other cases, it is added unintentionally.

Designers are trained to use representations that contain extended knowledge and part of the professional training of designers includes coaching them how to work with the extended knowledge of their sketches (Schön, 1987, Chapter 3). The ability to work with extended knowledge in design representations includes:

1) Create representations containing extended knowledge.

2) Live with the vagueness, uncertainty, ambivalence, and inaccuracy of such representations.

3) Read that extended knowledge and incorporate it in solving the design problem.

The general amount of extended knowledge in the representation through a successful design process gives an indication of the variety of solutions being dealt with in the various stages. During initial stages of the design process, designers have only a vague understanding of the design situation, which they then struggle to clarify. As they determine certain aspects and parts of the design solution, the extended knowledge is reduced. As the final representation is created and delivered to the client, the extended knowledge becomes negligible and is eliminated completely when the final product exists and serves as a complete, comprehensive, and absolutely accurate representation of the design solution.

Goldschmidt defines the term *figural concept* to describe "the congruity between a symbolic figural expression of concepts and given visual clues, which are to the specific observer (Tim), complete and coherent enough to suggest the concept" (Goldschmidt, 1991b, p 3.). In other words, designers are sometimes able to associate a complete concept with a symbolic (external) representation that does not express the whole concept to others. The notion of extended knowledge is manifested in Goldschmidt's notion of *figural concept.* Both notions *refer to* designers' ability to associate extended information and understanding with a given partial (external) representation.

Goldschmidt (1991) also shows imagery in design tools to be dynamic or interactive; that is, it changes in response to actions of designers who interact with it. Hutchins (1995) calls this quality the dialogue between designers and their notes (sketches).

I suggest that the extended knowledge state be composed of the following components:

1) Shared knowledge that varies between personal, professional, or public levels. This shared or background knowledge is based on conventions codes and symbolism that is shared among members of a certain audience and depends on their shared training (e.g. professional knowledge).

2) Situated knowledge that is based on the context of interacting with the representation.

3) Inherent vagueness and ambiguity. This rubric of extended knowledge depends on the type of scheme used to represent the information; in some cases, this scheme is not designed to eliminate vagueness. Examples of such a scheme are artistic drawing, sketching, and sculpture.

The advantages of using extended knowledge state are:

1) Allows designers to keep information in a flexible state and not commit to decisions until they are necessary.

1) The efficiency (speed) of creating the representation is higher than without enabling extended knowledge.

2) An improved ability to separate between modelling the raw data and modifying it at a later stage. Verstijnen et al., (1996) defines these two stages as *synthesis* and *modification*.

The preferred level of extended knowledge in representations through the design process is shown in Figure 3.8.

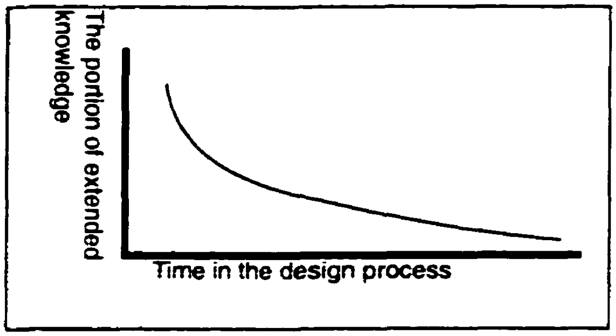

Figure 3.8: Changes in amount of extended knowledge in the design process.

The amount of extended knowledge shared by the audience depends on the diversity in that audience. Norbert Wiener (1954) shows that the connection between the size and diversity of the audience and the effectiveness of a language is reverse logarithmic, i.e. the more diversity in the audience, the less effective an item of communication is. This relationship is shown in Figure 3.9.

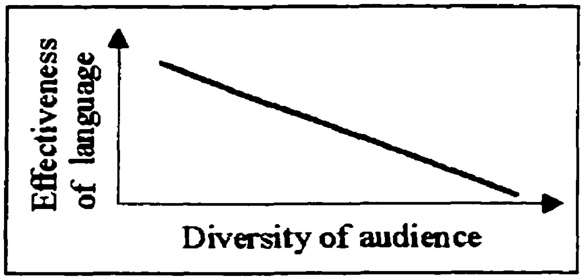

Figure 3.9: The relationship between the effectiveness of a language and the diversity of its audience

This section prepares the ground for understanding the basis of representing knowledge in design by describing the variety of representation schemes used in design from a theoretical standpoint. An important concept is introduced: a unique aspect in design is its reliance on extended knowledge, which permits exploration in different directions without being required to decide and commit even when expressing ideas.

3.6.1 Design Representation Schemes

Before we can understand how representations are used in design, we must define some terms.

According to Goel (1995) ***Representation Schemes*** are symbol-systems, languages, or coding systems used to code, store, and communicate information.

It is important to note that all representation schemes are limited, and that each representation scheme is more suitable for certain applications and less suitable for others. No representation scheme can accurately and efficiently represent all data possibilities.

Based on Goel (1995, p.5), and Goldschmidt (1991b)I suggest dividing representations into two types based on whether they exist inside or outside the mind of the designer.

Internal Representation Schemes (IRS) (or intentional symbol systems) are schemes that exist in the designer's mind. They are personal, intangible, and characterised by human cognitive processes and memory structures. These representations exist only in the designer's mind's-eye.

External Representation Schemes (ERS) (or physical symbol systems), on the other hand, are representations expressed by a designer into the public domain. They are therefore tangible, can be perceived by human senses, and could be experienced or shared by more than one person.

The transformation between IRS and ERS is done by formatting the internal data using a variety of schemes (spoken language, bodily gestures, drawn signs, etc.). The transformation from ERS to IRS is done by perceptual mechanisms and by deployment of cognitive filters.

As will be shown below, both directions of this transition are imperfect in the case of most people, as a result, they affect the content being translated.

The above statement suggests that both directions are imperfect, let us assume that it is false, i.e. that *both* directions ERS->IRS->ERS are perfect. If this would be true than it would mean that most people would be able to perfectly internalise any given external representation and express it in perfect accuracy. This is clearly incorrect, because most people are unable to perfectly replicate the *Mona-Lisa*, this proves therefore that not *both* directions are perfect. Let us now consider the two separate cases ERS->IRS and IRS->ERS in much the same way, if this was true, then

a) Most people would be able to either detect any close-to-perfect replica of the *Mona-Lisa*, in other words, perfectly internalise the external representation. This is clearly not true, otherwise all faked and reproduced art would seize to exist.

b) Most people would be able to produce two identical copies of any internal representation they may have. This is clearly false because most of us can see the differences between any 2 copies we try to make even though a shows that we are imperfect in detecting such differences.

Both a and b are clearly false, which proves that most people are unable to perfectly convert between external and internal representations.

My understanding is that the transformation between the two schemes may be effected by the following limitation:

1) Mechanical limitation: The inability to draw shapes or make gestures or sounds in absolute accuracy (e.g. limitations of eye-hand co-ordination of the human designer affects the accuracy of the produced drawings).

2) Convention limitation: The inability of conventional schemes to accurately represent subtleties of unique and novel situations often existing in design work (e.g. it is impossible to represent a specific colour verbally, without referring to a sample).

3) Time limitation: These limitations can be again divided into two types:

    a) Limitations caused by the static nature of representation schemes and the dynamic nature of the represented content (e.g. no static graphics can directly represent the motion of a bouncing ball; all ways of representing this motion will require the use of imagination or decoding)

    b) Limitations caused by the time it takes to produce the representation, it is often too long to capture all the content before the internal expression changes or degrades.

4) Knowledge limitations: The limitations caused by the level of knowledge required to encode or decode data (e.g. it is necessary to learn mechanical drafting in order to accurately read a mechanical production drawing).

The ability to use internal and external representation schemes in design must be acquired, and the skill level varies between novices and experts. A range that can cause additional reduction in the integrity and proficiency of the translations leads to multiple representations of a single situation. Such different representations are caused by differences in the applied methodologies and skill of application.

This notion corresponds with Goel who suggests that translations are not necessarily reversible is interesting, because it implies that the transformation from external to internal representations are not sufficient for accurately and definitely "decoding" it. For example, a sketch that was created to represent an internal mental image may yield more than one definitive idea when read.

We can conclude that interpretation of design sketches should be performed with attention to the above limitations, and can often yield new meanings when done without considering the contributions of additional data not included in the representation scheme due to extended knowledge associated with it. For example, understanding and perceiving the full meaning of an artefact must include some understanding of the creator and the process that produced it—a fact well known in art and design. Both IRS and ERS can have multiple representation schemes describing the same issue; internal representation schemes are the internal mechanisms of coding, storing, and handling information. The discussion of transforming between internal and external schemes can be divided into three topics: perception and sampling, processing and calculation, and learning and memory.

A description of internal representation schemes is given in Chapter 4. According to Tan (1997), the aspects of these internal workings that are important to the discussion on the design process are:

1) The limitations internal mechanisms pose on human competence to design.

2) The competencies of these mechanisms and their influence on preferred design practices.

3) The way these mechanisms contribute to creativity in design.

The subject of memory and learning was studied from many perspectives, including human problem-processes solving in laypersons (Wickens, 1992) and experts (Klein and Crandell, 1995).

Knowledge in design can be classified according to whether it is internal or expressed externally, and design is based on the interaction with our external surroundings; as such, it depends on the processes of perceiving and expressing information.

3.6.2 Types and Uses of Design Representations

There are many ways to view the different representation schemes used in design. One way is to divide them according to their format and media, such as 2D paper drawings vs. 3D digital animations. Other ways include the knowledge level of the intended audience and the level of accuracy and detail.

Akin divides the representation schemes used in design into two types: *preliminary design documents* (representations used for the preliminary design development) and *construction documents* (representations used to convey and communicate the design intentions to others). This is a clear division with one exception: in the case of group design work, where design representations are used for both development and communication of ideas and concepts.

An important notion presented by Akin (1986, based on Newell and Simon, 1972) is that some external representations reflect just a portion of the knowledge, with some or all the rest of the knowledge to be retrieved by additional processing. I would like to extend this notion to cases where the external representation reflects only a portion of the knowledge, some of which could be extracted by additional processing, some embedded in the organisation of the information (similar to Gestalt content), and some could be embedded in the knowledge of an audience that shares a previous background or understanding.

Human information processing capacity is limited. We can hold only four to eleven data items in our working memory (Miller, 1956) and then only for a limited time span. The only way we can deal with larger amounts of data is by storing them elsewhere, either in our long-term memories or outside our brains. External memories are seen as an extension of long-term memory, but they have different characteristics.

The accepted[34] characteristics of storing knowledge in long-term memory (LTM) are:

1) Knowledge is modified when stored in LTM; it is often coded in a way that reduces its content.[35] The mechanisms used to store the knowledge are also called learning mechanisms.

2) Access to knowledge stored in LTM is known to deteriorate in time.

3) Both storage and recall of information in LTM is performed using a specific perspective. Association connects to the information; recalling data about a house will give different results when related to "door," "window," and "heat."

4) LTM is personal and internal, and it cannot be used to share information with others.

However, the characteristics of external memory aids are (Hutchins, 1995a; 1995b):

1) Information is also transformed when coded or perceived. The mechanisms are different: external memories are perceived, not recalled; expressed, but not necessarily learned.

2) The information does not decay in time (unless misplaced or technically deteriorated).

3) Information can be searched using a variety of approaches and perspectives. Looking at an image can display a variety of perceived items, depending on the focus of attention and the level of detail being used.

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[34] The list given here is a combination of approaches to the subject by Akin (1987), Goel (1995), Goldschmidt (1989, 1991), Hutchins (1991, 1995), and Wickens (1992).

[35] The issue of LTM storage is discussed in detail in Wickens (1992).

4) External memory aides can (and often are) shared between people (and maybe even machines).

5) It is well accepted (Akin, 1987; Goldschmidt, 1989, 1991; Hutchins, 1991, 1992, 1995; Goel, 1995) that designers and others have an interactive "dialogue" with their external memory data. This seems to be pivotal when it comes to development of the represented information because when this dialogue takes place, data is being modified and a change occurs.

This section described the "internal workings" of representing knowledge in design. It shows the two type of representation schemes: internal and external, and describes the transitions among them.

The following section discusses the primary and most unique representation schemes used in creative design exploration: *design sketches.*

3.7 Design Sketches

The most prominent types of external memories in design are sketches. Describing and analysing human-sketch interactions is multidisciplinary in nature and requires combining knowledge from a large number of relevant fields with different perspectives, vocabularies, objectives, and limitations. The ill-structured nature of sketching is an obstacle in conducting observations and reporting scenarios scientifically. Sketching is a situated activity; it depends on the situation in which it is performed, thus, one must consider the environment in which it takes place. The difficulty of studying the interaction with detailed observations occurring within short time frames, combined with the complicating factors described in the previous chapters, explains why no studies were found to provide a complete understanding of this issue.

Before discussing design sketches any further, a working definition must be introduced. We might start by considering the Renaissance term *pensieri,* the Italian word for *thoughts* (Goldschmidt, 1992, p. 191). This term reflects the common use of sketches in design, which is to aid ongoing design thinking. The term was first used in the early days of the Renaissance and is still used to describe working drawings of designers and architects, as sketches are still considered to be a visual thinking aid for solving design problems. This definition excludes graphic illustrations, just a description of an image without ambiguity; thus, they do not support a progression of images during the designer's reflection process.

Goldschmidt (1991, p. 130) suggests that design sketches are loose and ambiguous by offering various directions of progress, whereas hard-line drawings are "more or less accurate, true to dimensions scale drawing, often executed with drafting devices such as rulers and triangles." In the case of this paper, tools are taken as drafting devices, producing hard-line drawings. This distinction complies with the understanding of the author of this paper. In other words, design sketches seem to be able to hold extended knowledge in design.

An additional distinction is also made here, based on the differences between working sketches and illustrations. The goal in the former is usually to depict an evolving idea or concept (as it is imagined or thought of), whereas the latter is to communicate a finalised (or fixated) visual concept to others. This discriminating factor is visible in the apparent "look" of the sketch and does not only exist in the intentions of the designer. Designers were found (Goldschmidt, 1991; Reiman, 1996) who prefer vague and loose sketches during their design work. There is even a technique for "loosening" a sketch, which is known as *pentimenti,*[36] and involves substituting a single definite line with many lines that are close in appearance. The term *pentimenti* not only refers to the technique of adding fussiness, it also represents the creation of multiple line drawing in the first place.

The notion of any advantages in using *pentimenti* as a design tool may be hard to understand at first. This raises the questions: what do designers find useful in vague sketches, and what attributes of these sketches is the cause of this usefulness?

Many researchers (Goel, 1995; Goldschmidt, 1991,1992; Suwa and Tversky, 1996) have tried to answer these questions. They conclude that designers use these loose sketches because this type of sketch allows them to explore the design-problem-space without committing to a single solution, and that they can discover new options that become apparent to them during or even after sketching.

Goldschmidt reports on the quality of using sketches to support thinking in cases where the designers have an image in their mind's eye, but this image evolves during the time they sketch. This notion suggests that some form of "computation" or analysis is performed outside of the brain; the shape can support indirect or unintended processing of the concept under development. This notion has much in common with the term *shape emergence* used by Mitchell (1990). Both of these terms suggest that something happens unexpectedly, either unintentionally (a mistake that leads to a better understanding or better design) or unconsciously (a rectangle of constant surface area, where increasing the length of one segment will result in a decrease in the other segment). This property of complex problems is often a result of the complexity of the system's constraints, and cannot be easily calculated in the designer's mind during sketching in "real time." There are other cases where emergence is possible, such as cases when the problem is composed

[36] An expansion of this term is used throughout this paper; *pentimenti* here includes both multiple-lined drawings and soft-lined drawings, where the latter refers to drawings which include wide lines as well as lines where borders are not clearly defined.

of multiple "work-domains" (Schön, 1984) or "design modules" (Goel, 1995). In these cases designers tend to jump from focusing on one domain to another, making them view the situation from a new angle, which in turn, allows them to discover new properties and new directions for progress.

Drawings is a general term that can be interpreted in many ways; some of them include basic graphical elements such as circles, arcs, squares, straight lines, etc., while others consist of other building blocks that are entirely different, in the form of *freehand* drawings. Freehand elements are drawn by hand without using rulers, guides, or templates and are usually generated in a quick and inaccurate manner. Because design sketches require an ability to be loose and ambiguous, most design sketches consist of freehand-drawn elements.

The term *design sketch* in this thesis refers to all possible elements that serve as a dynamic representation scheme, i.e. elements which can represent other objects, situations, qualities, etc., and offer the designer an ability to change in time. An example demonstrating this expansion of the term—described in Chapter 4—was found in the observation; the participant designer picks an electric box and uses it as a sketch element. At first, he relates to its overall size, then to its shape, and finally he uses a loose and rattling piece of plastic on it to simulate a set of three operating buttons. Defining the 3D object as a sketch describes its role. These ways of using 3D objects in design practices were analysed by Harison and Minneman (1996); however, they do not refer to these objects as sketches. They suggest (p. 430) that objects are used to "illustrate"[37] the following five properties in the design situation:

1) Appearance: surface properties.

2) Form: the shape of an object and its relationship to other objects.

3) Feel: tactile feeling, response to pressure and other types of interaction.

4) Material: the specific internal properties of the material.

5) Performance: structural, mechanical properties of the object.

To enable anyone to apprehend design sketches, they must be able to understand the visual language system consisting of a set of visual symbols—a set (finite or infinite, discrete or continuous) of visual symbols. Each is a basic building block and has attached

[37] The term *illustration* in this document refers to "fixed" drawings (or 3D objects) that are not intended to dynamically change in time.

semantic content and visual appearance, and a set of rules describing possible operations and transformations to be applied to the set elements. This is not to say that incomplete familiarity with a visual language system will necessarily lead to misunderstandings

The following description of sketches as a visual symbol system is given here because it imposes some limitations on the structure and the flexibility of sketches, as well as on the use of sketch elements in this paper. Most visual languages contain a rule that keeps the results of all operations in the initial set. This can be demonstrated in the example of Euclidean geometry, where all possible operations on all valid geometric objects result in a geometric object, which is guaranteed to still be valid. These operations can be divided into two main types: *binary operations* involve more then one element (e.g. a summation) and *unitary operations* involve a single element (e.g. rotation of an object). This attribute of symbol systems is called *system closure*.

Most studies to date (Goldschmidt, 1991, 1992; Hennessey et al., 1994; Suwa, 1996; and Verstijnen et al., 1996) have dealt with sketches of high levels of aggregation. None of these studies examined sketches at the single pencil stroke level and could not, therefore, study the elements, rules, or operations taking place at this level of detail. A term suggested here for this level of detail in time is *sketching time resolution*, defines the time detail in which most detailed operations and elements are described.

This section showed what design sketches are, their unique characteristics, and the ways of studying the interaction with them. It was shown that design sketches are a form of external thoughts, which use external memory devices to extend and enhance design thinking. The following section will discuss the interaction between the designers and sketches.

3.8 Interaction with Design Sketches

The strategy utilised in this paper suggests dividing sketching into two parts: the "reading" and the "writing" of the sketch. This division is an arbitrary one, in agreement with Schön (1984), who contends that the perception and action are inseparable and there is no way of acting without reflecting. Therefore, visual perception in its various levels is a part of reflection and directly influences actions.

The structure proposed by Verstijnen et al. (1996) for studying the interaction between the designer who generates and reads the sketch and the sketch itself, starts by dividing the interaction into three major parts: the motor actions of "creating and modifying" the sketch (i.e. the designer's output); the "reading" of the sketch (i.e. the designer's input channel); and the cognitive processing behind the interaction, which includes learning and remembering of data related to sketching.

Dividing sketching processes into these three parts simplifies the analysis of the entire process because each part differs from the others in the models and theories available for analysing it in the known literature.

Studies exploring the first part of the interaction—creating and modifying the sketch—are scarce, especially in the context of sketches specific to design practice (Goel, 1995; Goldschmidt, 1991, 1992; Hennessey et al., 1990; Suwa and Tversky, 1996; Verstijnen et al., 1996). Most of these studies consider either perceptual aspects of sketching (Goel, 1995; Suwa and Tversky, 1996) or the active aspects of sketching (Hennessey et al., 1994; van Sommers, 1984).

Verstijnen et al. (1996) analysed the design process in a high level of aggregation, giving some theoretical foundation for dividing design processes into steps: synthesis and restructuring. This study analysed the information and structure involved in these two steps, but did not analyse sketching at the required levels of detail and time resolution.

The papers reviewed here on this aspect are by Goldschmidt (1991, 1992) and Suwa and Tversky (1996). These studies seem to be incomplete in that they do not provide the necessary description of high level of detail and time resolution. Both of these studies take verbal expressions associated with design sketching to be the basic operation, even though each "design move" (Goldschmidt, 1991, p. 125) can be a set of many sketching operations.

Unlike in other fields, sketching in art and design is often (Goldschmidt, 1991; Hill, 1966) considered to be an active part of vision, since it allows the artist to examine the view and adds "depth" to the perception of the image. A partial analogy to this would be that note-writing is an active part of reading, as it lets the reader "digest" the read material while perceiving it. Again, this may be better understood if taken to be an analogy of perception-action in ecological psychology.

This part of sketch perception is mainly based on the approach taken by Goldschmidt (1991), who suggests a dialectic for sketching and divides "seeing" into two somewhat overlapping modalities:

1) seeing as: defined by cases where "the designer is...using figural, or 'Gestalt' argumentation" (p. 131), and

2) seeing that: defined by cases "When...the designer advances non-figural arguments to entity that is being designed" (p. 131).

These two modalities of "seeing" refer to sketching operations as a whole, and not only to perceiving the sketch, as the reader might expect when unaware of "seeing" viewed as an active part of vision. *Seeing as* is the important type for creativity, because it involves transforming the image into something else; for example, when *seeing* a space *as* a corridor of a house. In this example, the process of interpreting the data according to experience or professional training leads to a new meaning; this meaning can result in a different perspective of consideration, different grouping of elements, etc. This issue is crucial to the construction of the model and will be discussed in greater detail in Chapter 5.

The biggest advantage of paper sketches is obviously their ability to support multiple representation schemes simultaneously, with flexibility in switching between these schemes. This flexibility is hard to facilitate in computerised environments because every added datum removes freedom from the existing definitions, and changes that are possible at one point in time become impossible at a later time. For example, a square has 90° rotational symmetry; therefore, it is synonymous in both horizontal and vertical orientations. However, when it is stretched to a rectangle, it can no longer be rotated by 90° and appear unchanged.

Literature on sketching (Goel, 1995; Goldschmidt, 1991; Hutchins, 1991; Rowe, 1987) considers design sketching from a holistic perspective. This approach suggests that the designer-sketch system should be examined by looking at its elements and the reciprocal influences between them. Goldschmidt calls this type of sketching "interactive-imagery" (1991, p. 132) and Rowe describes it as an active "dialogue" between the designer and the sketch.

The concept of interactive sketching is based on the iterative nature of design sketching. Progress in design is achieved by sketching details during a given period and then perceiving the accumulated sketch. The time span of these periods ranges between fractions of a second and the entire duration of the design process.[38]

This section described the interaction between designers and their sketches, the following section will extend the discussion to the interaction among parts of these sketches.

3.9 Interaction Between Sketch Elements

In the previous section we saw that designers interact with design sketches as a dialog, supporting to emergence of new ideas. This section describes the interactions among

[38] The range of time corresponds with the three time scales described in Chapter 5. During the micro time scale, designers use their motor perception mechanisms to guide their actions, with little separation between moves and perception. The cycles in stroke time scale often involve repeated stroking, which is constantly monitored by the designer.

sketch elements[39] that allow these unique types of interactions. It is important to remember that this study is concerned with design sketching as part of design activity and is less concerned with the mathematical and syntactical relationships among shapes, marks, and objects in the sketch. These subjects are covered here for the sake of completeness, but will not be analysed in detail. The topics of syntactical and mathematical relationships and the rules governing the transformation of groups of shapes into new shapes are covered in greater detail in a field known as "shape-grammars" (e.g. Tan, 1990).

Table 3.2 compares the two types of interactions contributing to the emergence of new forms and ideas: the first type is related to the mathematical relationships and transformations of shapes and syntax between various sketch elements (Tan, 1990). The second type is related to the perceptual and cognitive transformations between the designer and the various sketch elements as described in the previous sections.

The interaction takes place in the representation of these elements (e.g. two pairs of parallel lines becoming a rectangle is a rule in a given shape-grammar), or in the perception of the sketch by the viewer (i.e. in the eyes of the beholder). This way of dividing between the two types of interactions correlates with the division between explicit and implicit (extended) knowledge described earlier in this chapter.

As a form of visual language, sketches have two relevant aspects: *visual attributes*, which determine their appearance and can be seen as the syntax of the sketch, and *semantic content*, which may require learning if based on a convention different from the straight-forward meaning based on appearance. For example, an icon of a house may look like a certain house or may be an abstraction that will require an explanation to the audience.

Table 3.2: The interaction among sketch elements according to shape grammars (Tan, 1990) versus the interaction between the designer and these sketch elements.

Intrinsic Shape Attributes	**Designers' Perception**
The rules governing the possible options can be prescribed.	The rules coding and decoding of optional "aspects" are personal and dynamic.
Different attributes in an image should (but do not always) match.	Various levels of interaction exist simultaneously.

[39] Sketch elements are parts and components that make a sketch. In other words sketches may be comprised of other (partial) sketches, objects, marks, etc.

Various shape "aspects" are possible; however, they should be specified if a definite meaning is to be conveyed.	An accumulation of attributes creates a perceived Gestalt meaning.
Aspect blindness is possible due to communication (bandwidth, noise, etc.) or representation (translation, coding).	Perception allows designers to interpret data in cases of missing or conflicting attribute data. This can cause multiple aspect reading. This often results in shifts due to semantic interpretation.

Goel (1995, p. 23) notes that symbol systems and representation schemes are based on a set of "characters" or token symbols. These symbols are purely syntactic elements that do have content and are only interpreted by their *known* reference to content. An example of a set of "characters" is the set of letters in the alphabet. Representation schemes may be based on any number of symbols along with the content they refer to; Goel says that knowing the symbol system is recognising the symbols and knowing what they refer to.

This attribute of visual languages is important to sketches; it allows a shift in levels of aggregation of information, both in generating the sketch and in "reading" it. The flexibility of visual languages used in sketching explains how multiple lines in *pentimenti* can be combined into a single line. This is also how lines are combined into an outline or a texture. This ability of sketch to scale and combine data becomes more powerful when an infinite set of symbols is offered.

Design sketches are not constructed only from a finite set of discrete elements, such as digits or letters, and any attempt to describe them using digital combinations would be inaccurate and incomplete. Further, images described by a sketch cannot be fully and accurately translated into a set of forms and shapes with a one-to-one correspondence (Goldschmidt, 1991). The extended portion of information lies in the context and the background knowledge possessed by the sketching designer at the time he or she generates the sketch.

Ivan Sutherland writes in a retrospective article (1975, p. 75) discussing Sketchpad:

> An ordinary draftsman is unconcerned with the structure of his drawing material. Pen and ink or pencil have no inherent structure. They only make dirt marks on paper. The draftsman is concerned principally with the drawing as a representation of the evolving design.

Sutherland argues that paper sketches are not structured; this statement is true only from a pure syntactic and mathematical perspective, as the structure in design sketches is not easily apparent and formulating it definitely not a trivial task. Unlike written verbal language, sketches do not require a sequential or even directional order in their elements to hold or convey content. A sketch can be composed with no apparent order and still stay true to its meaning. Ideograms, which are used in Chinese and other oriental languages, use pictorial symbol systems that can be read with less attention to the order in which they appear. The symbol representing "big" and the "mountain" can be used as both: "big" + "mountain," and "mountain" + "big" and still mean the same grammatically. The ability to combine two or more ideograms into one new ideogram is an attribute of these symbol systems that does not exist in ordered symbol systems. The combination of ideograms does not have to be allowed at all times but usually occurs in historical perspective. Changes in the appearance of ideograms can occur over time because of shifts in meaning of the combination or of the separate elements.[40]

Design sketches often display dynamic qualities including: having a flexible number of meanings. from none to many; the meaning associated with a sketch often changed over time as a reflection of the changes in context and environment, and in some cases, even dramatically (as described by Goel, 1995; Goldschmidt 1991, 1992; Finke et al., 1988; Suwa and Tversky, 1996). Design sketches may have a broad range of intended audience, a single designer at a specific point in time to an entire design team composed of many people with personal perspectives and from several professions, while still able to convey large amounts of information. Design sketches can be generated relatively easily and quickly, and much better than any other way (Hennessey, 1994; and Verstijnen et al., 1996). Goel (1995) suggests showing that design sketches contain more information than computerised-drafting drawings.

Are sketches a unique representation scheme? Goel (1995) provides us with an even more strict positive answer: Sketches are not only a symbol system, they are a *complete* symbol system. Sketches are capable of describing a complete set of objects, relationships and rules, and can be compared with other symbol systems such as spoken language and Euclidean geometry. This suggests that sketches are powerful enough to describe our surrounding world; however, sketches have a code that needs to be learned and understood. It also means that sketches are capable of conveying information efficiently. A single symbol or sketch can convey a large amount of data that can only be decoded or understood by other experts who share that rapport. Vicente (1997) argues that this coding of information in expert knowledge is often based on an abstraction hierarchy. It is well known that chess players remember game settings in a coded way which allows them to "see" and understand them by recognising their distinguishing qualities. Unlike other representation schemes, design sketches are flexible and are able to support multiple

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[40] For example: the Japanese term *Karate* was changed in appearance from a combination of *Kara* and *Te* meaning "foreign fist techniques" to *Kara* and *Te* meaning "empty-hollow fist techniques", which expresses the Zen aspects of the martial art in this meaning (Funakoshi, 1973, p. 4). The process of composing new symbols as a combination of simpler ones is called *Lu-Shu* in Chinese and *Ri-Kusho* in Japanese (Yang, 1997).

schemes for representing information. This is useful to fulfil the need for multiple perspectives in solving the range of aspects of the design problem. An example that demonstrates this advantage is the use of written notes on design drawings along with CAD-generated information and soft sketches; here, a combination of schemes offers a more complete picture of the design situation and allows the designers[41] to analyse it from different perspectives concurrently.

According to Goel (1995), a group of symbols becomes a symbol system when it includes a set of symbolic elements and operands, a set of rules that describe how they should interact with each other, and the results of these interactions. In order to fully analyse a group of symbols, one must have a way of finding the elements that make that group and the relationships among them. Based on Goel's description, design-sketches are composed of simpler visual, graphic, or text elements. The question is: can we divide sketches produced in a design session into the components they are composed of, and how?

In the observation described in Chapter 4 we will need to determine what sketch elements exist in the sketching surface, so that we can refer to them in the analysis. How can we find the sketch elements of a given sketch? I agree with Saund and Moran's (1995) approach, suggesting that sketches be divided into their elements based on three factors:

1) The time at which these elements were created. At high levels of detail, this partition yields strokes.

2) The location of these elements on the drawing surface. Climbing to higher aggregation levels is done by grouping elements within a bounded territory in the drawing surface.

3) The meaning associated with sketch elements. Lines that define an outline are combined to generate a single outline; then several outlines that describe different perspective views of a single object are combined to a single 3D representation of the object.

Representation schemes in CAD systems are restricted to a single type, mainly because it is very difficult to maintain the structure in the representation of a model when shifts between options are allowed, e.g. the Form-Z modelling program allows designers to shift between several levels of topological hierarchy (generate a cube as a single "primitive"

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[41] The design team here can be either one person or a group. The ability to support multiple coding schemes becomes even more important when there is more than one person involved, since each expert in the team observes the information from a different point of view and interacts with it using his/her specific representation language.

and then modify its vertices, segments, or faces simply by shifting the hierarchy mode). This often causes problems as users take advantage of this feature to "correct" cubes in order to fit their envisioned shapes. What often occurs is that the "modified cube" does not mathematically qualify as a cube, because one of its faces is no longer planar. This type of problem does not occur in sketching because the meaning of the sketch is flexible and resolved in the audience's perceptual mechanism.

Design sketches allow designers to interact with design information while having the flexibility to create and modify them quickly and easily. This flexibility allows designers to create and discover unanticipated new ideas in combinations and modifications of their sketches. Goel proves that the flexibility and density of information in design sketches allows for better and more diverse (creative) design practices when compared with computerised drawing.

This section has shown that design sketches are useful for design exploration because they are able to completely represent design ideas in a rich (dense) and dynamic fashion, as well as offer high levels of flexibility in interpretation and interaction. The following section concentrates on this interaction between the designer and the sketch.

3.9.1 Designers and Sketching

One of the biggest strengths of paper sketching is its flexibility in supporting a variety of design strategies ranging from pure "top-down" to pure "bottom-up." An additional advantage of design sketching is its ability to allow parallel development threads simultaneously. This description was derived from observations of industrial design practices and from the personal knowledge of the author with additional qualitative analysis of empirical observations described in Chapter 4.

A different approach to analysing design processes is given by Verstijnen, Stuyver, Hennessey, Leeuwen, and Hamel (1996). They divide designers' use of sketches into two separate stages: first, the stages of form synthesis, and second, the restructuring of existing forms. Verstijnen et al. also argue that the main strength of using sketches in industrial design lies in the restructuring stage, where more difficult calculations are used. Intuition at this stage suggests that this observation is true in paper sketching, but this strength has so far been lost in the digitisation processes of sketches.

Hennessey (1994) compared paper sketching with CAD modelling in the initial stages of design and concluded based on his empirical testing, the efficiency of sketching is not evident in CAD modelling.

As shown by Hennessey (1994), CAD systems require designers to devote much of their effort to the task of modelling, including envisioning and translating the design data into

CAD formalism. As a result, CAD modelling often increases the cognitive load for designers; in comparison, sketching seems to require less cognitive resources[42].

Intuition suggests that CAD is unable to compete with paper sketching for the following reasons: computerised sketching imitates paper sketching under large constraints from hardware and software; paper sketching offers flexibility in switching between representation schemes with no effort, whereas computerised sketching is confined to a single limited scheme; there exists a limitation derived from the need for ease in programming of mathematical transformations; and operations in computerised sketching do not make use of human visual processing, such as approximations and noise elimination.

Unlike freehand sketching, computerised sketches are much more confined in the ways they are sampled and the mathematical mechanisms used to translate them to digital codes. Representing sketches digitally requires a clear definition of format. A sketched line may be represented as a series of points each marking the location of the "pen" at given time intervals, a series of segments which connect between these points, or a series of vectors which make a function describing the drawn path. Most currently available digital drawing tools require the user (the designer) to set the characteristics of the digitising method.

Freehand sketching uses a rich interface mechanism (e.g. the way an art pencil draws on *Canson* paper) known to experienced designers, whereas, digitising mechanisms[43] tend to be more difficult to master. These digitising mechanisms tend to reduce the fidelity of translation for the sake of efficiency, which results in the loss of the richness of the sketch.

3.10 Summary

To summarise this chapter: Design problems are typically ill-defined, ill-structured, and complex—often involving many aspects. Thus, the processes used to solve design

[42] The *Secondary-task technique* (Gopher and Donchin, 1986) is a method for evaluating the cognitive workload created by a (primary) task. The workload is measured by assigning the participant a secondary task, to be performed concurrently with the primary task, and by measuring the fluctuations in the performance in the secondary (when it is performed without the primary task). For example, when people perform a complex arithmetic calculation, they tend to talk slower than without performing the calculation.

[43] The term "digitising mechanisms" here includes both hardware and software components of the interface.

problems tend to display similar characteristics, in other words tend to be complex, ill-structured, and often wicked.

Design practice has evolved under the constraints of human information processing and the reality of limited resources common to all designers. Designers cannot deal with massive amounts of detail simultaneously, which leads them to divide design problems into smaller, more manageable, portions and to shift their attention between these separate portions. The common strategies in design practice include detailed planning of systematic design, such as the one proposed by Simon (1969). Using rules of thumb can help guide the design process, such as the heuristic rules suggested by Akin (1987), as can intuitive and free-flowing unexplainable design practice based on professional artistry, such as reflection-in-action in design described by Schön, 1983 and 1987.

As mentioned, the complex and multifaceted nature of problems in design requires designers to shift their attention between different portions of the problem. These shifts create a wicked structure in design processes, where different threads of thought are interlaced together. Rowe (1987) examines this characteristic from the perspective of design practice (and not from that of the design problem). He calls that behaviour *episodic* design, referring to the apparent episodes that are defined by the shifts between dealing with different portions and aspects of the design. According to Rowe (1987), the episodes in design behaviour reflect both the inherent logic of the design situation and the procedure used to solve it. This suggests that design domains that correlate with the focal points of these episodes are directly correlated to both the design problem and the performed design procedure. This notion is the basis for the 4D model introduced in Chapter 5.

Knowledge in design includes both specific and generic knowledge. This knowledge is sometimes shared by many people and sometimes known just to a single individual (the designer). The knowledge can either be *internal* (existing in the mind of a person) or *external* (visible and accessible by others). These two types are not mutually exclusive; in many cases, an external representation includes a portion that can be interpreted only by enquiring further than its obvious meaning or by using additional knowledge and understanding, such as professional training. This type of knowledge is called *extended knowledge* (Simon, 1969). This chapter expanded the definition on *extended knowledge* initially defined by Simon to include knowledge and information associated with objects and elements through the context they are used in through the experience and background shared by their audience, and by the vagueness and ambiguity inherent in the element.

The concept of extended knowledge in design representations is pivotal to this study, because it serves as an indicator of progress in the process. Design problems are ill-defined; as a result, initial stages of design typically include large portions of extended knowledge. As the design progresses, more details are resolved, defined, and represented; therefore, these stages typically have less extended knowledge. The design process ends successfully only when the design representation includes enough details with sufficient accuracy and can be used to produce and manufacture the design, when extended knowledge is minimal.

Extended knowledge is important to creativity in design, because a representation in design becomes interactive (e.g. interactive imagery) only when there can be a difference in its interpretation at different iterations. When no extended knowledge is associated with a representation, it has a constant meaning during a series of iterations. When a representation is interpreted according to the extended knowledge associated with it, there is a chance of seeing new meanings depending on changes in context, audience, or point of view. These changes can result in the emergence of new concepts and ideas, hence supporting creativity.

Experience and knowledge allow designers to design effectively while interacting with complex situations without having to interrupt the flow in order to process large amounts of detail that compose the situation. This is achieved by representing situations according to key features and reacting to them. The resulting structure of design representations is therefore hierarchical, where a set of details (features) make a unit that represents a complete situation. Designers behave according to professional know-how that often includes heuristic rules-of-thumb. However, some design behaviour cannot be expressed or explained except by performing a task; this professional know-how is called knowing-in-action. In cases of insufficient performance, designers need to stop and reflect on the situation before they progress their design. This latter behaviour is called reflection-in-action.

There is a close relationship between reflection-in-action and extended knowledge, because designers often need to reflect-in-action in order to interact with the extended knowledge. This suggests that incorporating extended knowledge in representations is paramount for professions like design that are based on reflection-in-action.

Akin (1987) describes the structure in design knowledge. He shows that it is based on hierarchy, where several information elements are grouped to create a single, more complex, information unit. Rassmusen argues that hierarchical structures in human cognition are based on two dimensions: *abstraction* and *aggregation*. He shows that these two dimensions are connected and that an increase in abstraction also results in an increase in aggregation. When applied to design, this notion suggests that complex design-situations may be equally described as abstract structures and as aggregated structures. This is useful because it offers an alternative to Akin's structure that suggests reducing complexity of design information only by aggregating elements and not by abstraction.

Design sketching is a complex activity involving motor actions and perceptual and cognitive processes and is commonly seen as the primary tool used in creative exploration processes in design. What makes it such an efficient tool? The answer to this question has three parts:

1) Design sketches—the outcome of design sketching—are powerful and unique schemes that can represent many different aspects of a design at a desired level of detail and a needed level of abstraction, and can contain a variable amount of extended knowledge.

2) Design sketching is not limited to linear formulation. A designer can sketch a given aspect of the design, switch to representing a different aspect and a different component of the design, and then return to complete the initial portion, all without harming the integrity of the sketch, the design, or the process of sketching. This ability is unparalleled by any other representation tool.

3) There is a flexibility to separate between semantics and syntax in design sketching, because the content of sketches may include some extended knowledge that does not necessarily have a constant meaning (the meaning is partially in the eyes of the beholder). This allows shifts in meaning with little or no change in the appearance of the sketch; such shifts will be shown to be important to creative processes in design.

During their training, designers need to develop a holistic vision of their work, to perceive it at various levels simultaneously. This *direct-perception* allows them to interact much more efficiently with high levels of complexity in the design without having to interact with the associated details. Operations in design sketching are often performed directly at the higher levels and much of the complexity is removed. This cycle of operation—called the *perception-action cycle*—is effective only when short time spans are involved. When the time between perception and action is increased beyond a few minutes, the knowledge in the working memory decays and the cycle is broken.

A close analysis of literature reveals that most of the theories reviewed in this chapter share a common understanding that describes the interaction between designers and their sketches, based on high levels of perception and their professional and life experiences. As demonstrated in this paper, all of this relates back to the notion of *pensieri*, in which design sketching runs parallel to human thought and cannot be separated from it, even though that would make scientific life much easier.

Design sketches are dynamic; their content and appearance evolves during the process of sketching. This is not a trivial concept, because unlike other representations, design sketches evolve unexpectedly, depending on the context and perspective used to interact with them.

Sutherland examines sketches from a mathematical perspective, which led him to argue that they are not structured. Taking into account human perceptual mechanisms when examining design sketches suggests the existence of a structure. Adding aspects of semantics and dialectics draws an even more pronounced sense of structure to design sketching.

All the qualities of design sketches described previously point to the fact that sketching offers a unique channel capable of conveying a wide range of possible types of representations in a dense format that it is currently the best channel to support creative and artistic endeavours. However, these strengths of sketches can easily become disadvantageous when sketches are used such that elements or disorder in sketches complicate the communication. Another mistake is using sketches to create and convey data in a situation that requires communication with great accuracy; in such cases, sketches create more difficulties than benefits.

Design sketches are a unique means of representation. Design sketches are actually a combination of elements from different representation schemes, ranging from physical objects and formal drafting items through graphical notes, and from visual symbols to idiosyncratic doodles. This would make sketches flexible enough for representing a wide range of data types necessary—according to Rasmussen (et al., 1994)—for working effectively with multiple design domains and levels of abstraction This quality also makes sketches a powerful scheme for supporting creative endeavours such as design.

Some important differences between traditional and computerised sketching include the fact that digitisation reduces the richness of sketches, computer representations require a single meaning to sketches, and the translation between motor actions and the resulting sketch is more directly perceived in traditional sketching. This results in more accurate sketching in traditional methods. Goel shows that the richness (density) and flexibility of information in design sketches improve the diversity and speed of design activities.

An additional aspect not found in literature is the examination of sketching by observation of motor actions directly. Most studies tend to resort to verbal testimonies analysed using grammatical methods. The results of such observations are then used to explain *all* aspects of sketching, including motor actions. This seems to be a misconception of the latter operations, and seems to limit the level of detail or resolution of sketching processes.

The discussion in Section 3.9 also argued that structures associated with design are often based on decomposition of design situations according to problem-domains and on the perspective of designing (Goel, 1995; Rasmussen et al., 1994). The structures may be associated with the design situation in different ways ranging from its design problems and processes to its related representations. Describing hierarchical structure in design knowledge and representations is seen as a useful tool for analysing and aiding design.

The concept of extended knowledge—a consequence of studying the structures in design representations—introduced in the chapter is important for understanding the unique characteristics of freehand sketches. Extended knowledge cannot be represented in currently available digital formalisms because it is not a static representation.

It is suggested that an important part of design activity is based on professional artistry that cannot be accurately described or taught. This artistry includes both motor and cerebral activities, and cannot be replaced by computerised tools.

The following chapter describes an exploratory observation that was used to add to understanding collected from literature.

4. Exploratory Observation

After reviewing design theories in Chapter 3, it is apparent that no single theory is able to completely describe the nature of design problems, design thinking, and design activities. The goals of this project are to describe design processing and activity[44] in a way that could provide some directions to creating a useful and usable CAID tool, and to support creativity in design by providing a suitable means of representation. All this led me to conduct an observation to look for ways of combining the understanding from literature with studies of specific design sessions. The goal of this observation was to use qualitative protocol analysis to explore design activities and processes in order to describe the representations used in design work and the way they are used. I suspect that these descriptions will be useful for defining a more complete computerised design representation scheme, and later describe a mechanism for interacting with it.

This observation was also intended to study traditional design sketching and to explore the processes used to create them, in attempt to understand the reasons for its effectiveness in supporting creative design exploration.

Protocol analysis[45] was chosen as a basic methodology for the observation, because of its known ability to provide a means of studying cognitive aspects of design practice. It is currently the most common used methodology for analysing design processes (Cross et. al., 1996; Suwa and Tversky, 1996).

The methodology used includes three changes to classic protocol analysis: the data includes graphic information describing the sketching surface, the data includes verbal descriptions of visible actions performed by the participants during the session, and the coding scheme used in the analysis phase was applied only by the author and was not repeated by others (for validation).

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[44] Design activity refers to specific actions within the more global design process.

[45] The methodology used in this observation is based on the original protocol analysis methodology developed by Ericsson and Simon (1984). Nigel Cross and the Design Research Society (DRS) have recently advocated (Cross et al. 1996) the use of protocol analysis as an important tool for analysing design activity. In their document, Cross et al. also suggested some changes to the classic protocol analysis in order to accommodate the unique requirements of design practice.

4.1 Goals of the Observation

The observation was originally intended to examine the design process from three main aspects: information representation in design, operations performed in design sketching, and cognitive aspects of design sketching.

This research was designed to verify the intuitions and substantiate the selection of reviewed theories, provide additional understanding of the process of design-by-sketching, attempt to find the unique characteristics of sketches and sketching in design, and examine design practice in search of its detailed repetitive operations. The attempt to search for repetition in detailed operations originally came as a result of thinking that design can be described as a series of "common, simple, and mechanistic" operations. Evidence for such operations was not found in the observation.

During exploration and analysis of the recorded data, there appeared to be a pattern in the design behaviour, more specifically in the behaviour during the emergence of new concepts and ideas. Designers tended to change the way they dealt with the design situation. This change in behaviour was not anticipated, and in order to achieve the overall goal of the observation it was decided to modify the original analysis and to investigate the phenomenon, in an attempt to better understand creative design activity and the role of sketching in it. The new objective was to find a connection between the emergence of new design ideas and the design behaviour immediately preceding it.

4.2 The Participants

The study included three industrial designers who voluntarily participated in the experiment. They were asked to answer a short questionnaire to provide a general description of their educational and professional backgrounds. The goal behind the questionnaires was to place these individual designers within the common perception of the industrial design profession.[46]

Participant A has a Bachelor degree in Architecture, and a Master of Environmental Design (Industrial Design) degree. He has seven years' experience as the industrial designer of a small, award-winning design consulting firm. He is currently the sole industrial designer in a team of marketing, engineering, and research individuals.

Participant B has a Diploma in Industrial Design, six years' experience as a designer and four years' as modelmaker. He currently works as an industrial designer and a product manager in a small consulting firm offering concept-to-production solutions.

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[46] This was needed because there is no qualifying requirements to practice design; therefore, the need to demonstrate basic qualifiers common to an "industrial designer."

Participant C has a Diploma in Fine Arts (Sculpture), a Master of Environmental Design (Industrial Design) degree. He has seven years' experience as industrial designer and product manager. Participant C is currently serving as an industrial designer and manager of research-and-development in a medium-sized company. He usually manages a team of four to six members. Participant C testified that he usually uses CAD during all stages of his design work and does not usually use much freehand sketching in its narrow definition. He suggested that he usually prefers sketching over computer prints.

4.3 Procedure

The observation was composed of three design sessions. In each session, the designer was asked to answer a short questionnaire and then given a brief (Appendix C) description of the hypothetical design problem (design a wearable computer to be used by automobile technicians). The directions were to divide the thirty available minutes between concept design (five to ten minutes) and detailed design (twenty to twenty-five minutes).

The observation was conducted under constraints of budget, time, and availability of participants, all of which had implications on the experiment and the results, reducing its validity. The following problems were recognised:

1) The number of participants was low, eliminating any use of the data for quantitative or statistical analyses.

2) The study was conducted in an obtrusive fashion, i.e. the participants were aware of the experiment being held at all times. This probably affected designers' actions and caused differences between the recorded behaviour and the participants' regular (or natural) behaviour. The participants described two such factors during and after the experiment procedure:

   a) Participants were required to design while "thinking aloud." Thinking-aloud tasks are known (Cross et al., 1996; Ericsson and Simon, 1984) to disturb participants' ability to design because of the increased workload. The explicit demand for constant verbal testimonies was reduced ten minutes into the experiment with Participant B. this change resulted in a great increase in his visible productivity.[47]

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[47] Lloyd et al. (1996) also experienced this phenomenon when they examined the possibilities of using verbalisation for analysing design activity during the Delft workshop. They found a correlation between the cognitive load from visible tasks on the verbal rate (i.e. number of words per minute) during design practice.

b) Participant A commented that he is used to designing by himself as part of a "self-conscious process" and the mere presence of observers disturbed him and his ability to design.

3) Unlike in the observed experimental sessions, design work normally involves long periods of time for "digesting" the problem, familiarisation with the subject matter, and exploring directions to solution. This was known during the planning of the experiment, but no way was found to remove the problem without affecting the results.

4) It was realised that each designer has his/her own social style of work; some work in teams, while others work alone. The experimental design left some flexibility with the experiment-facilitator, allowing him to adjust the communication to increase the comfort of the participants while trying not to affect the results. In practice, Participant C preferred a discussion style, talking to the experiment-facilitator throughout the experiment; the solution here was to reduce the amount of response provided by the facilitator to a minimum.

The observations were conducted at the designers' own studios, in hopes of trying to sample "normal" behaviour more accurately. Two video cameras were used: to record the drawing surface, and to record the behaviour of the designers at work. Technical problems of mounting cameras did not allow capturing the drawing surface at the zenith (directly perpendicular to the surface); instead, an "over-the-shoulder" angle was used. The shooting angle resulted in segments where the participant's hand or shoulder obscured the view of parts of the sketching area, often blocking view of the actual point of interest such as the tip of the pen touching the drawing surface. In such cases, there was an attempt to use images of lower quality from the second camera.[48]

The sketching session involved the following non-computerised traditional sketching tools:

1) Drawing surface: a selection of papers (various sizes, textures, and other properties) was provided for participants.

2) Drawing instruments: a selection of drawing tools, i.e., pens, pencils, markers, and brushes was allowed for participants' selection.

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[48] Sessions one and two included long segments of such obscured view, this was detected when the tapes were initially viewed on-site before session three was taped. The viewing angle was adjusted for session three, and the image quality improved considerably allowing for detailed analysis.

3) Templates, rulers, guides, etc.: all these were allowed even though they are not expected to be used very much throughout the observation.

4.3.1 The Assignment

The design problem given to the participants was selected because it involves all the common features of design problems as given in Chapter 2. It is wicked (includes several interconnected sub-problems), ill-defined, and open-ended. This problem requires the participants to deal with a variety of components from a range of aspects including an ergonomic problem of attaching objects to the human body in a way that offers good convenience and usability; a variety of engineering aspects such as electrical, mechanical, structural, and production problems; aspects of defining the design problem and structuring it, including problems of dividing the system into sub-systems and connecting them into a complete product; aspects of marketing, aesthetics, and cultural diversity of users.

4.3.2 Role of the Experimenter

The role of the experimenter in this study was to allow participants to engage in "regular" design activity. This statement suggests that designers should have the ability to act as if they are in a real-life design situation and should not be lead by the experimenter or limited by him/her. This approach suggests the following behaviour from the experimenter:

1) The experimenter attempted to minimise his or her influence on participants' actions, by not suggesting or emphasising solutions, not asking guiding questions, and not limiting designers' actions.

2) The experimenter attempted to simulate the real-life situation by providing the (planned) background information. The scope of available background information was pre-determined and shown in the assignment (Appendix C.)

3) The experimenter was often required to act as a *listener* in order to make participants feel more comfortable. For example, Participant C is used to working with others, and required the experimenter to respond by acknowledging statements and keeping eye contact. On a small number of occasions, this somewhat conflicted with the attempt to not influence the participant.

4) The experimenter was also required to encourage designers to think-aloud. This was usually done when participants were quiet for a longer period of time. It became apparent that Participant B found it difficult to verbally express his thoughts as he was designing. At this case, the experimenter chose to reduce the pressure on him and allow him to express himself less than originally expected.

4.3.3 *The Recording Procedures*

The design sessions were captured using two video cameras:

1) the first camera (S-VHS professional camera) was used to record the (drawing) sketching surface. Due to technical constraints, it was impossible to capture the drawing surface without spatial distortion (i.e. we could not mount the camera perpendicular to the surface) and without obstructing objects (e.g. the hands or shoulder of the participants).[49]

2) the second camera (VHS 8mm home cam-coder) was used to capture the designer, his gestures, physical movements and his expressions. This camera could not be used to also produce a second detailed view of the drawing surface, because of its quality and resolution.

Both cameras were also used to record audio, which was used to synchronise the two tapes when viewed.

The recording produced a large amount of data, including a mixture of verbal descriptions, physical gestures, graphical images and written text; this data needed to be transcribed into a single format.

4.3.4 *Transcribing the Protocols*

The method used to transcribe the recordings is based on the methods described in Cross et al. (1996). The tapes from the two video cameras were synchronised—by matching a sound of a hand clapping—and then played simultaneously. The tapes were viewed repeatedly using an off-line video-editing suite, which allowed for detailed and accurate transcribing of the protocols. The video capturing equipment was not able to produce a time stamp on the tapes; therefore, a time code was assigned to each statement or a design move based on the related reading from the VCR counter. The designers were briefed on the design assignment, they were allowed to review it with the experimenter and to ask questions. No additional information was supplied beyond the design brief, but minimal clarifications were allowed.[50] After briefing, the participants were instructed to start the design session and the experimenter clapped his hands to set the time code (the clapping sound was used to set time code to 1:00:00.)

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[49] As described below, this technical difficulty was the reason sessions 1 and 2 could not be used for detailed analysis.

[50] The clarifications were allowed because the experimenter was simulating the role of a client, which would provide similar clarifications in a "real" session.

The verbal testimonies were transcribed *verbatim*, and noticeable physical activities or gestures were verbally reported. The counter reading was typed as time code. The appearance of the drawing surface from the video-recording, at a given time, was manually reproduced. This was done because no technical option was available for capturing a snapshot of the drawing surface (A photocopy of the actual final sketches is given in Appendix E.)

After initial on-site review of the tapes from session one and two, it was decided to adjust the viewing angle for session three. The amount of obstruction of view was reduced considerably in the third session, allowing for detailed analysis. Sessions one and two were reviewed and transcribed, but it was decided not to use them for detailed analysis due to inferior and insufficient data. The data collected in sessions one and two did not have a clear view of the drawing surface this made it difficult (and often impossible) to analyse the participant's behaviour. As a result of this technical difficulty, the data from these sessions was transcribed but was not used for detailed analysis. The initial (non-detailed) analysis of participant behaviour of these sessions did not produce any obvious differences from session three. If found, such differences would suggest rejecting the finding from the analysis of session three.

This section reviewed the procedures used for collecting and preparing the data for analysis. The following section describes the methodology used to analyse this data.

4.4 Observation Methodology

The study and analysis of industrial design professional practices has included many research methodologies. The nature of the design field resulted in a need for examining its practice from many aspects, ranging from philosophy and cognitive science (Goel, 1995; Goldschmidt, 1991, 1992, 1996; van Sommers, 1984) to psychology (Smets, 1995). Some studies examine the human social interaction (Tang, 1989; Cross and Clayburn-Cross, 1996; Cross, 1997).

Design activity includes a multitude of visible and invisible actions and objects. The goals here were to select a small number of variables that could describe these elements and to analyse the collected data and report the results in a coherent way.

To achieve these goals, we need to establish a coding scheme that will help classify the data, analyse it, and report the results. Such a scheme should be able to represent the situations occurring in the process. This is a difficult task in the case of design sessions that tend to include many different information types represented in a variety of schemes. Appendix D reports the observation protocol for session 3.

The coding scheme used in this study includes three variables: the verbal testimony given in a design move, the existing drawing surface during that design move, and the series of operations around it.

From these variables, another four dimensions are extracted: the representation scheme used in the move, the design domain involved in the design move, the level of abstraction used to view the design situation, and additional information that can help describe the move in its context. These variables and dimensions are given as they were taken from the video records of the session and commented upon.

4.4.1 Segmenting the Protocols

After protocols were transcribed, they were segmented into separate design statements or *design moves*[51] (Goldschmidt, 1991). The design moves were delimited by the start of a new (not connected) sentence or by a physical activity performed between verbal testimonies. A time code was assigned according to the counter reading at the beginning of the statement or physical action.

4.4.2 Coding the Segmented Data

After the recorded design activity was transcribed and segmented, it was coded according to four dimensions: Time, Design-domains, Abstraction -level, and Representation-Scheme. The objective of analysing and coding the collected protocol data was to explore possible connections between patterns found in the design activity and the emergence of new concepts and ideas. In particular, the analysis attempts to find a tie—at the time of occurrence—between the emergence of a new idea and any changes to any of the above described dimensions within a design move or the one immediately preceding it. The detailed coding procedure is described in section 4.5.1.Once coded, the observation data was analysed and scanned for patterns in behaviour around the time of emergent instances.

4.4.3 Analysing the Coded Data

The methodology of examining the protocols used to understand more about the relationship between the emergence of new concepts and jumps between different design domains, representation schemes, and abstraction levels was as follows:

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[51] The term design move is used here similar to the way it was used by Goldschmidt (1991). A design move is a basic "act of reasoning which presents a coherent proposition pertaining to an entity that is being designed" (p. 125).

1) The coded protocols were reviewed to detect emergent ideas, concepts, or features. The criteria for finding an emergent idea was whether or not this idea was mentioned before in the protocol. This method is similar to commonly used methods (e.g. Edmonds, 1994; Goldschmidt, 1991).

2) The second stage was to map the three dimensions in the time interval near the emergent instance. The time interval was divided to design moves according to the method suggested by Goldschmidt (1991).

3) At this point, a search for a jump is conducted, i.e. the information in the three dimensions was compared, and when a difference was found, a *jump* was said to have occurred. The search for *jumps* in one or more of the dimensions was conducted in the current design move or the one prior to it.

This section describes the methodology and the technical procedures used to code the design sessions. The following section describes the application of this methodology on the recorded design protocols and the analysis of the coded data.

4.5 Analysis of the Protocols

Data produced from sessions one and two was not fully analysed because of technical problems: the camera angle due to space constraints in the designer's studio obscured by the hand of the designer, so changes in the drawing surface were hard to track. In view of the poor quality of the footage recorded in sessions one and two (Participants A and B), it was decided to concentrate on analysing and reporting the results of session three (Participant C).

Goel (1995) suggests that representations could be interpreted only by using the connection or relation to the context in which they are used. This context includes domain specific training and knowledge, as well as the immediate context of the representation. The descriptive terms used for refer to the design-domains, representation scheme, and abstraction level—in the following section—were determined using some domain specific knowledge. After this being said, it was clear that the coding of these headings would be subjective to some extent. This was chosen instead of trying to choose objective terms, which would be less effective in reflecting the design situation without any domain knowledge.

The following section describes the methodology and procedures used to code the data collected during the observation, for analysing design activity.

4.5.1 Coding of the Protocols

Before describing how the recorded data was coded and how I obtained the terms used to describe the three dimensions of the design situation for each "design move" (Goldschmidt, 1989), let me review the definition of each of these dimensions.

Design-domains – this dimension reflects the interaction between the designer and the design situation by examining the "current" focal point in the design problem space and the perspective used to interact with it. As we saw in Chapter 3, designers tend to focus on selected parts of the design situation rather than the entire design problem space, and also tend to examine the design problem space from a variety of perspectives. A perspective indicates the combination of the prioritised[52] design aspects being applied to a given component(s) of the artefact being designed.

Abstraction-level – this dimension reflects the level of granularity. In this sense, the term corresponds with Ballay's (1987) use of "grain size." Abstraction-level encapsulates two separate divisions: according to functionality (i.e. means-end relationships) and according to components (i.e. whole-part relationships). This dimension is used here to describe the level of detail in the above described design move.

Representation-schemes – this dimension reflects the mechanisms a designer uses to code and express the concepts for the above described design move.

To determine what representation scheme is being used at a given point in time, we need to answer the question: "what is the mechanism used to handle[53] the information?" The answers include top-view drawing using rules of mechanical-drafting, a verbal reference to a sample physical object (the designer's waist), or a graphical icon used as a symbol representing "a stick figure."

It follows from the description given in Chapter 2 that the design domain at a given point in time can be determined by answers to the following questions:

1) What component of the design is the focus of attention?

2) What aspect of the design situation is being attended to?

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[52] Rowe (1987) states that the design problem space in a given design episode is evaluated according to a particular heuristics and that designers often rely on different heuristics during different episodes.

[53] The interaction with representation schemes is bi-directional, including encoding information and decoding it. This suggests that the term "handle" may take one of two meanings here; it can be encode-represent or decode-interpret.

3) What is the perspective (professional or otherwise) of viewing the design situation?

Because design domains are structured hierarchically, the answers to these questions can take a layered form. For example, at 1:13:15 in the observation described later in this chapter, Participant C says, "This is good in terms of accessibility to the object. Y'know I can really see...a three button pad here and doing my thing." Participant C deals with the button pad of the main unit from the aspect of accessibility and ease-of-use, and the object is viewed from the user's perspective. This design domain will therefore be described as (Design Domain = system/main unit/button pad/user perspective/accessibility and ease of use).

The Abstraction level (AL) was determined by answering the following questions:

1) What portion(s) of the design is being handled?

2) What level of detail does the designer interact with: a group, a subsystem, or a set?

3) Does the designer interact with the details or with an aggregated combination thereof?

The difficulties in expressing these dimensions in words are:

1) Designers may consider a given design situation in a variety of ways. In fact, many (e.g. Akin, 1987) consider formulating the design situation to be an integral part of the design activity, which tends to affect its outcome. This suggests that one cannot pre-define a set of options capable of labelling all the possible instances of the above-described dimensions.

2) Much of design activity is internal and personal, and the instances of the three dimensions are not directly and explicitly stated by the participant. This required the analysis to obtain some of the details indirectly.

These difficulties cannot be avoided and, therefore, affected the procedure of obtaining the terms used under the three dimension headings.

The methodology used for obtaining the terms used in the observation results under the different headings is:

Design-domains – the terms were chosen by combining the answers to the above mentioned questions. The participant often examined the design situation from a particular professional perspective. When this occurred the perspective was indicated. For example, at time=6:54, "Ergonomics–usage" was used under the design-domain heading. These terms were selected because the aspect of the problem being attended to is the "usage" of the designed-entity and this aspect is seen by assuming the ergonomic professional perspective. The participant does not interact with a specific design-component at the described point in time; therefore, no additional terms are used. As seen in this example, the different terms related to the (professional) perspectives, components, and functions are all separated by dashes.

Abstraction-Level – the terms were chosen to best capture what part of the artefact, representation, or design situation is being attended to. The level of granularity or the name of the part (of the related artefacts) were chosen to reflect this heading. For example, in Time=7:21, Participant C describes a volume between an area of his body and the designed entity. He refers to the "hip-torso area" of his body as a single part (without dealing with its details) and the volume it defines in relation with the main-component of the design device. Again, the device is considered as divided into its components and the participant is only referring to the main (later also called CPU-component) as a complete entity. The term given under the Abstraction-Level heading is "Body-torso," which indicates the part of the body in focus and "component-main unit" that indicates the part of the device in focus. The volume is being considered here (by the participant) at a level of granularity related to the two entities that define it (i.e. the body and the part of the device).

Representation-schemes – the terms used were selected to describe the "mode-of-output"—as Goel calls it—used to represent the design move. For example, in Time=7:21, Participant C refers to an area of the human body (referring to the body of a prospective user) by touching that area in *his* body and saying "that space". He therefore represents the body area by using his body as a physical example. The term used under the Representation –scheme heading is Physical object-his body's shape-volumes-human–waist–side.

Another example of assigning the terms describing the representation scheme, at time=6:54 the designer uses a two dimensional schema representing a lateral view of the human hip-torso area. In the same example the term used to reflect the abstraction-level was torso-hip, which represents the granularity of the components and representation by naming the part of the human body attended to at the time.[54]

A detailed transcript of session three is given in Appendix D and copies of the produced sketches are given in Appendix E.

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[54] The reader can see here that the torso-hip is the part of the human (user) body observed here from the ergonomic-usage perspective and represented in a lateral two dimensional lateral sketch. This complete example shows that the combination of the three cells in this row of the table yields an overall picture of the design situation at time=6:54.

The data collected during session three is presented as follows:

1) The verbal testimonies are given with reference to the time they appear.

2) The motor operations are described, with the synthesised view of the relevant sketching surface.

3) The analysis of the design domains, representation schemes, and abstraction levels relevant to the situation are given in a table format.

4) The segments of the protocol given here were selected because they show examples of cases of emergence resulting from different cases of shift between design domains, representation schemes, or abstraction levels.

The segments shown in this section were selected using the following procedure:

First, the protocols were reviewed in an order to detect emergent concepts or ideas, and isolate the instance of emergence. An emergent concept or idea is defined (similar to Edmonds and Moran, 1997) as a concept that was not previously mentioned in the protocol. After such concepts were detected, the protocols found in their close time proximity were analysed. The associated design domain, representation scheme, and abstraction levels where determined using the questions described above. After these attributes of the design situation were derived, it became possible to determine whether any changes occurred in them. Whenever a change in one or more of these attributes was found it was noted that a "jump" or a "shift" has occurred. Clear cases representing *jumps* or *shifts* found near emergent instances were then described in the following section.

4.5.2 Detailed Analysis of Protocols

This section contains the actual analysis of the verbal protocols that were recorded during the observation (with Participant C).

The following case shows a shift in both design domain and representation scheme:

At time=1:6:57, Participant C says "I go and lie on my side" (feels his side). The answers to the questions: "what part of the design is under discussion, in both the physical and the functional sense? And what perspective is adopted in the discussion?" yield the active design domain. In this case, Participant C assumes an ergonomics perspective-he considers the location of objects-from the aspect of interference with posture. The scheme used to represent the situation is: perspective view sketch of the proposed object

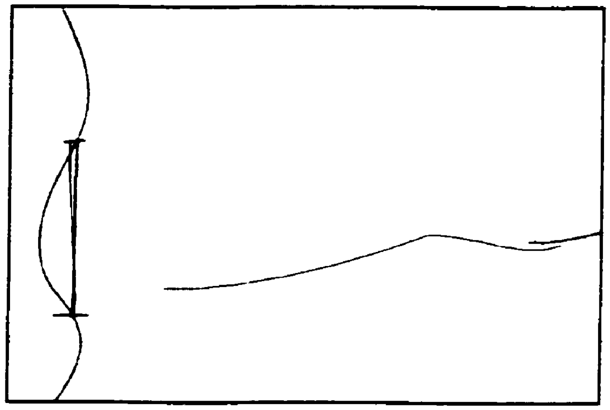

Figure 4.1: A 2D curve schematically representing the hip/lumbar area.

At time=6:54, Participant C says, "what I can do actually... if I've got sort of the hip area here" (sketches the lateral section of the hip area; see Figure 4.1) (7:04) "and then" (feels his hip and shoulder.) Analysed in the way, yields the results shown below in Table 4.1.

Table 4.1: The four *dimensions, related to the volume and location of the product.*

Time	Design domain	Representation scheme	Abstraction level	Shift
6:54	Ergonomics–usage	2D–schema–lateral shape of hip area[55]	Body-torso	
7:04	Ergonomics–forms to fit to body	Reference to physical object–his side of torso–3D shape.	Body-torso-hip area	RS and AL
07:21	Form–volumes, space between body and ground	Physical object-his body's shape-volumes-human–waist–side	Body-torso area, Component–main unit	RS and AL

At time=07:21, Participant C says, "if I can use *that* space, I've got *that* space" while he is feeling his waist area. He is referring to his waist as a physical-sample describing shapes-volumes, the hip/torso area representation scheme he is using. He then draws a

[55] Here we see an example which includes a representation which can be interpreted as a section/outline of either a side view or a front-view of the human waist/lumbar area. This is made possible by the selection of a schema which is ambiguous in its representation. Note that the only way we can distinguish between the two options is by context, initially Participant C feels his side, (i.e. waist) but later he feels his back (i.e. lumbar area).

curved line representing that part of his body. Then Participant C draws a vertical line touching the schematic-curve. The result in the shift in RS is a new concept: contain the main system component in a curve of the body at waist/lumbar height. Participant C recognises the ambiguity in the representation but does not remove it. He prefers to keep it undecided until time=13:29 where he says, "OK, for this exercise that's where is going" and decides on his side/waist.

At time=9:35, Participant C says "yeah he'll have to be fairly thin" (sketches) "go down through there," (sketches) "and come along a little more" (sketches) "around here" (sketches) "so what's he gonna do here" (touches his waist.) Then Participant C says, "he's gonna come along there and sorda do that" (sketches pentimenti.) Then, (switches pen to thick) at this point in time Participant C comments "so then, once I sort of gotten that far ... then I sorda go over it again to try to clarify...so I have a better understanding of what that object is and how that would fit in there." At this point, he reflects while sketching "ehm, in terms of servicing this thing...ehm, how often do you need to get into this object?" Experimenter: "not often, rarely." Then Participant C says, "OK, so both power to it, battery that we can charge externally?"

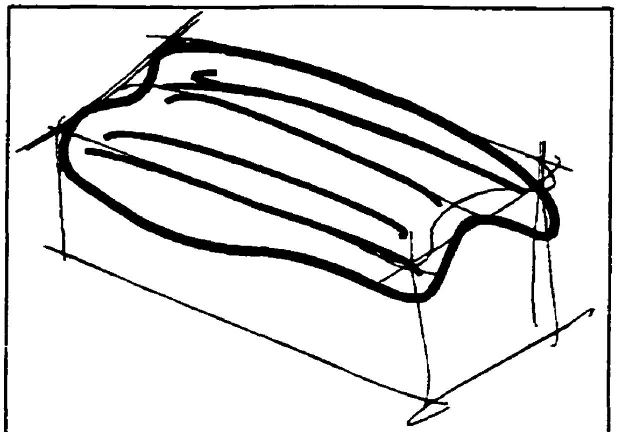

Figure 4.2: The sketch representing the external form of the main component.

Table *4.2: The results related to the form of the main unit.*

Time	Design domain	Representation scheme	Abstraction level	Shift
9:35	main component–ergonomics–object shape–fit to body	perspective drawing–3D external structure–shape outlines		
9:45	main component–shape	reference: physical object (his body)		DD and RS
9:49	main component – ergonomics–object shape–fit to body	loose exploration drawing–perspective–3D shape outline		RS
9:56	Ergonomics–object shape–fit to body	perspective drawing–3D shape outlines–reduced ambiguity	Main component	RS

Time	Design domain	Representation scheme	Abstraction level	Shift
10:29	entire system–interaction–procedures–service–frequency	verbal discussion	Entire system	RS and AL
10:39	power supply system–interaction–service	verbal discussion	Subsystem–power supply	DD and AL

Here we see a shift in design domain as well as is abstraction level: attention is shifted from shapes to interaction procedures. And a **new concept** emerges: a chargeable battery sub-system is defined.

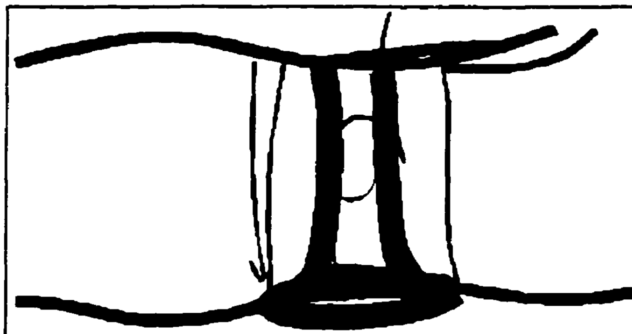

Figure 4.3: The strapping system

At time=18:40 Participant C says, "I'll have a strap going off" moving to "that object (the strap) will take off, whatever buckle type" a shift in abstraction level between two elements of the same system. "have to be a low profile buckle "(feels waist) cause we're running into some problems" "maybe we'll tuck the buckle in" **new feature** = the shape of the buckle becomes tucked in the hard drive enclosure, the buckle is still a separate element.

Table 4.3: The analysis of protocols related to the strapping system.

Time	Design domain	Representation scheme	Abstraction level	Shift
18:40	Belt system–strap shape general	Loose sketch–perspective view.	Strapping–system elements–strap	
19:00	Belt system–buckle shape general	Loose sketch–perspective view	Strapping–system–elements–buckle	DD through AL
19:08	Shape–general	Reference to physical object (designers' body)	Torso and whole strapping system	DD
19:10	Shape–ergonomics	Orthographic–view top-appearance	Torso and whole strapping system	DD and RS

Participant C then points to the connecting line between the buckle and the belt "I'll make that... that buckle and I'll bring him into this face" "so, so the object swings over and actually grabs onto the belt (demonstrates the swinging and fastening action) so, so, that whole fastening system is part of the object...right OK, so that'll stick underneath there" **new concept** the buckle disappears and becomes a part of the enclosure.

Table 4.4: The analysis of the protocol regarding the buckle component.

Time	Design domain	Representation scheme	Abstraction level	Shift
19:14	hard drive–face–shape–geometry	Schema–components in orthographic–view–front	Details in main component	
19:24	Strapping–fastening system–composition	Orthographic–view–top	Details in main component and strapping system	AL, DD, and RS
19:28	Fastening object–buckle–shape–usage–function	Orthographic–view–front	Main component of the strapping system	DD, and RS

In this example, an emergent idea is found near shifts in all three dimensions.

The conclusions of applying the analysis procedure on the protocols yielded the following results:

1) It was established that, as expected, the designers in the observation displayed episodic behaviour, where the definition of design domains follows the common characteristics of design episodes and is therefore parallel to it.

2) Jumps between design domains, representation schemes, and abstraction levels during shifts between contiguous design moves were empirically found to be in close time-proximity with emergence of new concepts and ideas.

The analysis of the verbal data revealed an interesting finding related to the nature of representations used during design practice. Participant C appeared to use various levels of privacy in the way he represented the available information. He was writing short text notes that were clear and expressive to him, but were ambiguous and made only partial sense to other observers (e.g. the experimenter). Participant C appeared to be aware of the benefits and limitations of these representations, and even commented on the subject. At time = 1:29:06, he sketches a little doodle and says, "I'm not gonna draw a head ... forget it! Imagine there's a head there." The participant is aware that his sketch element will not be clear to other people, and yet he uses it because to him is it fully descriptive and does not require him to spend much time drawing. This finding is in line with Goldschmidt's (1991b) notion of "figural-concepts," which refers to the congruency between symbolic expressions that encapsulate and convey an entire concept to their creator. This notion is a clear demonstration of extended knowledge and provides some reasons for the efficiency and effectiveness of design sketches.

This section describes the analysis based on the verbal protocols recorded during the observation. The following section describes the analysis of the non-verbal data collected during the observation.

4.6 Analysis of Non-protocol Data from the Observation

This section includes all the findings from the observation that were not found via analysis of the verbal protocols. These findings are patterns of design behaviour detected during the multiple reviews of the video recordings made during the observation. As such they are not based on rigorous procedures and methodologies and may not have the same level of validity. These findings are reported here because they seem important for understanding the complete nature of design activity, and may be researched further in the future.

In the observation, sketching appears to have generated a relatively lower cognitive load[56], as it is often performed in parallel with looking at the existing state of the design and talking about it. Sketching often seems to offer a means of enhancing concentration and the designer's sense of vision, just as was suggested by Hill (1966). This has serious implications on the time factors in the sketching process, as it allows designers to simultaneously review and refine their sketch.

During the review of the video recordings of the observation, it was noticed that, designers sometime stop sketching, observe the sketch they just produced, and then continue sketching again. At other times they seem to observe the evolving sketch without stopping. This variety seems interesting to me because it shows that designers are able to observe and perceive their sketches without interfering with their motor activities. This may indicate that in the latter cases designers sketch in a different manner and may be attempting to perform a different task. I suggest dividing sketching activities into two different of types or modes based on the above finding.

The first type or mode, which I would call "Continuous sketching mode," is described by cases where designers continually monitor their sketching operations as they sketch,

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[56] This understanding is based on considering design sketching to be secondary to the overall design (problem solving) task. The theoretical foundation of this understanding is found in the *Secondary-task technique* (Gopher and Donchin, 1986).

without stopping (i.e. without stopping the sketching activity in order to observe their accumulating outcome).

The second type or mode, which I would call "Non-Continuous sketching mode," is described by cases where designers sketch and occasionally stop to examine the accumulated results. These reflections can occur while mechanically sketching over existing sketch elements. For example, at 1:11:24, in the observation in Chapter 4, when participant C completes sketching a complex shape and wishes to fix[57] or select some of the elements, he selects a wider point pen and traces over the elements, selecting only parts of them. The result of this oversketching procedure is usually more refined and more determined representations of the design.

A detailed exploratory review of the observation also revealed that designers often sketch loosely in a way that seems effortless and less conscious. During these sketching periods, they are able to talk, calculate shapes, and evaluate relationships. This unconscious sketching seems to enhance designers' ability to focus their attention and organise their thoughts. This type of sketching is often performed over existing sketch components, when designers trace, review, and slightly modify the existing representation. I call this sketching operation *oversketching*. I would argue that *oversketching* is an example of the perception-action cycle, because when designers oversketch, they perceive the existing sketch through their sight, sound, touch, and their kinaesthetic senses like ordinary sketching; thus, they add the "sense" of sketching as a part of seeing (Hill, 1966). The modification of the sketch is therefore an action influenced by directly perceiving various levels of the sketch. It is important to note that this type of sketching is displayed only by expert designers and artists, and is a part of the artistry of sketching or the knowing-in-action of design sketching.

After describing the results of analysing the observation in this section, we should summarise and review the findings. The following section provides the conclusions from the entire observation study.

4.7 Conclusions

The results of the observation study described in the previous section show that *jumps* in one or more dimensions of activity in a design situation (i.e. Design domain, Representation scheme, or Abstraction level) occur within close periods of time around the emergence of new concepts and ideas. This does not prove the existence of a causal relationship between the emergence and jumps, but it does show that a connection exists.

[57] "Fix" here refers to making a fixation and not making a correction.

I believe that this finding is important because it establishes a connection between the attributes of activities within design situations and the creation of new concepts and ideas.

This observation also shows a way of describing design activity in terms of design-domains, representation-schemes, and times at various levels of detail or abstraction. This description is useful because it organises design moves—and with it the progress in the design process—according to the focus of the designers' attention and their design-perspectives (i.e. according to design-domains) and according to the way they are represented. This way of organising the process allows us to sort design activities according to each of these dimensions. It is expected that sorting design activities in such ways will enhance the appearance of threads of design thought (i.e. reveal the links between design moves) and the emergence of new ideas. The outcome of organising the design process according to these dimensions can be depicted graphically in a 4D model, explained in detail in the next chapter.

In addition to these results, it was also found that designers were sketching in two different modes:

1) In a continuous sketching mode, were they continuously sketch and experience their results without stopping and reflecting.

2) In a non-continuous sketching mode, were designers periodically stop and review the accumulating results of their sketching activity, and their evolving design representation.

It was also found that designers appear to sketch-over existing sketch-elements with little effort. This type of sketching, which I call *oversketching*, seems important because it shows that designers are able to use design-sketching in an efficient manner, shown by the fact that *oversketching* appears to add little interference to the overall design task. *Oversketching* seems to be relevant to the overall subject of this project because it may allow us to detect cases of good fit between designers, their design task, and the interaction with the CAID tool that was introduced to replace the efficient design-sketching.

After describing the conclusions from the analysis of the observation, we can now continue to introduce a method of visualising design activity according to design-domains, abstraction levels, and representation-schemes found throughout its progression.

5. The Emerging Theory

Chapter 3 reviewed the theoretical foundations and terminology for describing design activities and the representations they include. Chapter 4 described the empirical study of specific design activities. The theoretical review is a description of generic design practice, whereas the empirical study describes the characteristics of design practices as apparent in a specific design session. Chapter 3 reviewed theories that express the connection between the nature of design problems (i.e. design problems being ill-defined, open-ended, complex, and often wicked) and the common structure of design practice. It is shown that design activity is composed of a series of ***design episodes***, where each episode focuses on a particular portion of the design problem. Designers appear to decompose the design problem into smaller partial problems. They then temporarily focus their attention on a particular portion. These portions of the design situation[58], called *design domains*, allow designers to overcome the complexity of design problems by devoting their attention to a less complex problem during a time interval. Chapter 3 reviewed theories suggesting that designers employ a different set of mental models (Rasmussen et al., 1994) or heuristics (Rowe 1987, following Schön, 1983) during each of these intervals or episodes. We can see that these design episodes are an important characteristic of design activity because they seem to be the tie between the nature of design problems and the nature of design activities. Other studies (such as Goldschmidt, 1989, 1991; Suwa and Tversky, 1996) have already examined the connection between related design-segments in design activity and creativity. However, no study to date proposes a method for sorting design activity according to the portions of the design situation considered during each of these design episodes, which can increase the visibility of the emergence and thread of development of individual design concepts.

Chapter 4 described a method of coding design activities according to the four dimensions: *Time*, the designers' centre of attention (called *Design domains*), the level of aggregation and abstraction (called *Abstraction level*) of the design domain in-focus, and the method of coding and conveying the information relevant to that domain (called the *Representation scheme*).

The following chapter proposes a graphical model for visualising design activity according to the four dimensions described above. This four dimensional (4D) model may allow us to view (and review) design activities according to the centre of attention in each time interval. As we will see in this chapter, this model provides us with a better view of the evolution of design situations during the examined activity, the scheme used to

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[58] The initial design problem may be given in a design brief, but tends to often be complex, ill-defined and open-ended. The design situation is the current temporary state of the design problem(s) with the accumulated understanding of it and the evolving partial solution(s) to it.

represent their related information, and the navigation through the design space (i.e. the navigation along the abstraction level and the design domains).

Chapter 4 shows that the content of design activity may be sorted along time according to specific design-domains or representation-schemes. It will be shown below how sorting the view of the activity along these two dimensions may allow us to visualise the progress in a specific component of the design-entity or the use of a specific representation mechanism.

This chapter proposes methods for visualising the development of design concepts based on the design domains attended to during episodes in design sessions and on the schemes designers use to represent these concepts. The level of granularity in decomposing each design situation was traced and described because—as described by Goel (1995)—it influences the possible directions for development of appropriate design solutions. This way of visualising design activities is proposed because it allows us (as shown in Chapter 4) to comprehensively depict design activity. The added benefit of using the proposed model is its ability to trace the evolution of specific portions of the designed product along with specific aspects of the design activity and the particular perspective used to generate and interact with the evolving design representation.

Chapters 3 and 4 show that design activity is usually composed of multiple episodes, each of which focuses on a specific design domain and may be represented in different ways during the process. By definition, different design domains reflect the perception of the different parts and aspects of the designed product, and therefore could be used to trace design activity. The design representations produced during the design process are traced because they may be used as visible evidence of the design thinking processes, which are often invisible otherwise.

This design domain dimension of the model is used for depicting the generation and evolution of multiple concurrent design ideas. Many other theories describe the design process according to analysis of chronological design events or moves (e.g. Linkograph). Unlike these theories, the 4D model describes the process based on the evolving set of design domains and representations relating to the designed product.

According to Rowe (1987), Schön (1983,1984), and Rasmussen et al. (1994) design domains evolve in correspondence to the perception of the design problem (i.e. defining and describing the still non-existent product); thus, it cannot be comprehensively defined a priori. Designers often solve the problem of working without a problem definition by creating a vague and loose concept of the desired product based on the limited information provided, and then refining and evolving the design domains as they go. This is in line with the findings from the observation described in Chapter 4.

The model is based on the concept of decomposing design problems into design domains or modules (Goel, 1995) and does not attempt to explain *why* designers demonstrate episodic behaviour. It proposes a way of tracking the emergence and evolution of design concepts with their association to design domains and representation schemes. This is done in order to learn more about the contributing factors to creative behaviour in design in general, and the contribution of the representation schemes used in particular. The design activity is traced by examining representations used at each point in time and the design domains being attended thereto.

The model depicts the flow in design thought by tracing the shifts in the focus of attention during a series of design episodes, the visible records (e.g. sketches) produced in it, and the operations associated with the creation and modification of these records. The design is depicted as a series of design situations changing over time. These situations change from being the perceived design problem, as may be found in the initial design brief, to the design solution as given to the client at the end of the process.

This model is created to describe and direct design processes, and can depict design processes and representations. This model might, therefore, be used as a tool for visualising design problems and activities, and may be used to direct design processes when structure is found in the product or system being designed.

The model is comprised of four dimensions—time, representation schemes, abstraction levels, and design domains. The following section details the meaning, construction, and importance of the design domain dimension.

5.1 Design Domains

The primary component of this model is a set of design domains that describe both the design problem and the perspective from which it is considered. Design domains were chosen as the basis for the model because they are the portions of the design situation considered during the individual segments that compose an entire design activity.

As discussed in Chapter 3, Akin suggests that different information or knowledge is communicated to different audiences at different stages of the design process, where each audience is concerned about specific components and aspects of the design. There is no single language or representation scheme that can facilitate all these communications; thus, designers use a variety of representation schemes, each suitable for a specific audience and specific information. Akin does not emphasise in his work that these different communication audiences and channels represent different aspects and components of the design situation.

Interestingly enough, many researchers appear to associate design activity with some sort of decomposition of the design situation into smaller, simpler design issues that can be individually considered and resolved. Let us closely examine some of these examples. Vinod Goel (1995) uses the term "design modules" to describe the parts or components of the designed entity being considered. Rasmussen et al. (1994) use "problem domains" when referring to the different aspects designers consider during their work. Donald Schön (1983) examines this subject from a slightly different approach. Instead of looking at what designers attend to, he chooses to examine designers' "work domains" or the different perspectives designers use while considering design situations. This short comparison shows ways that designers can defuse the complexity in design situations. They can decompose the situation according to the system's components, the different design aspects, or the different possible design perspectives. All of these different options are valid, and the 4D model proposes a way of describing design activity along all three options.

As described above, design domains refer to design issues; they are defined by dividing a design system (i.e. a design or situation) into the simpler and smaller design systems they are composed of. The term "design domains" is based on Schön's *work domains*, Goel's *design modules*, Rasmussen's *problem domains*, and Peter Rowe's (1987) concept of "design episodes" that divide design activity into the (shorter) time intervals in which a single portion is considered. *Design domain* is defined as the portion of the design situation the designer attends to during a specific episode. Based on the definitions given by Goel, Schön and Rowe, the specific design domain is determined according to three relationships:

1) The *part-whole* relationship: This relationship is used to decompose the design system into its parts (usually its physical components). Part-whole decomposition is often applicable to physical systems. In the observation[59], a wearable computer is considered to be composed of three elements: the headgear, the CPU/hard drive, and the battery/power supply components. This allows the designers to isolate and interact with smaller portions of the problem and leave the integration to the latter stages.

2) The *means-end* relationship: This relationship allows designers to decompose the system into its functional components. Once these are defined, designers can selectively deal with them selectively and concentrate on smaller parts of the design system. The top level in this decomposition process usually yields the goals of the design. For example, in the observation, designers examine the designs they suggest according to the four requirements specified as goals (i.e.

[59] This decomposition into three parts is naturally based on only one level of granularity, where the system is perceived to be composed of three parts. Later in the observation, each of these parts was perceived to be composed of smaller granules. (e.g. power supply component was seen as having a detachable battery and a casing).

end requirements) in the brief. They consider manufacturing, ergonomic, aesthetic, and usage aspects of their design solutions. Designers integrate all the different aspects by prioritising them and concentrating only on some of them.

3) The *perspective* relationship: While relationships one and two are inherent to the design situation itself, the third is the relationship between the situation and the designer performing the design task. Designers seem to consider design situations from a variety of perspectives, each of which embodies a prioritised set of design aspects and design portions. The term perspective was chosen, because designers in the observation appear to view the design situation from various perspectives. Each of these perspectives embodies a prioritised set of aspects related to particular components of the situation. These perspectives often allow the designer to employ a mental model by playing the role of a certain persona. For example, the participants in the observation examine the possible operation or usage of the device by simulating the role of the user. (12:19) "...I probably wonna reach through and find some stuff."

The observation described in Chapter 4 shows that a combination of the different design aspects, components, and perspective offers a complete and comprehensive way of describing design activity, because each system is composed of part(s) that serve function(s) needed to achieve the desired goals and can be considered from certain perspective(s). The model shows the design system by analysing the way designers sort components according to these three relationships during the process.

The model is applied directly to design processes and design components, perspectives are detected by tracing the representations used in the process. Each piece of information must appear in the model when it becomes necessary for describing the design situation. In each appearance the representation is needed by one or more members of the design audience. Therefore, it is part of at least one communication channel and represents an aspect of the design a member of this audience comes to solve. If a piece of information is not communicated to, or used by, anyone throughout the entire design process, then it is useless to the design process and irrelevant (i.e. the description of the design situation is complete without it). On the other hand, the representation schemes used in each of these communications are equally useful in describing the design situation.

5.1.1 Describing Design Situations

As reviewed in Chapter 3, Akin (1987) and Lawson (1990) argue that design knowledge and representation can structured hierarchically[60] according to functional (constraint based

[60] Goel (1995) refers to C. Alexander who suggested that design situations and knowledge may not always be structured in a tree like hierarchy, he gives the example of a city as a

or means-end) analysis and according to means-end or part-whole methods of analysis. Akin uses the term *domain* in referring to the various chunks in the representations of the design situations; he does defines *domain* to be based on part-whole partition, while I prefer to use domain as based on both whole-part and functional decomposition and in relation to the perspective decomposition. This definition allows me to investigate the organisation of representations as they are perceived by the designers who created them, and to follow their thread of attention or thought. This thread is seen as necessary for tracing their thoughts and for detecting the emergence of new concepts and ideas.

5.2 The Proposed Model

The model proposed here is intended for exploring design practices and not intended to give a recipe for "good design". It should be viewed as a description of design activities by organising design processes using the representations generated, and the design issue being attended to as the design processes are worked through.

The model is comprised of four dimensions:

- Design Domains: as mentioned above, are the primary dimension of this model, and serve as the root for all structure shown by it.
- Time: describes the progress of time in the design activity.
- Abstraction level: represents the level of detail at which designers interact with the design, at any given time.

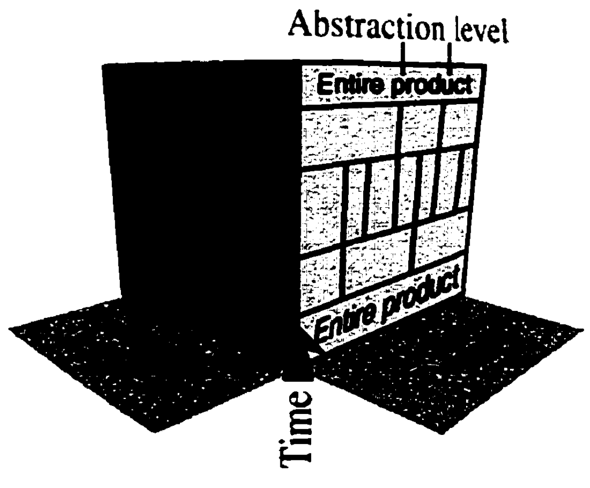

Figure 5.1: The 4D model of design.

- Representation schemes: describe the mechanism used to encode and decode the design situation.

Goel (1995) notes that all these dimensions are interconnected based on the problem itself. While some redundancy may exist, no dimension can be completely described by others. Different design domains correspond to different audiences, each of which possesses a unique language and means of communication. That concept is important to

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design entity which he suggests is structured as a semi-lattice and not according to a tree like hierarchy.

this thesis because it provides a connection between the axis of design domains and the axis of the representation schemes used in dealing with these domains, and can, therefore, help us understand the requirements from representation schemes used in design and CAD.

Another justification for structuring the model according to these dimensions comes from human problem-solving methods and apparent episodes in design behaviour (Rowe, 1987). It has been recognised (Klein and Crandell, 1995) that experts create a mental model of the problem they are facing, based on their experience and understanding, and then construct a solution based on recognition of key features in the situation. Each mental model includes background knowledge and understanding often associated with procedures for solving parts of the problem. These procedures do not have to be an integral part of the mental model; however, a link between the model and these familiar procedures is common. The mechanism for coding the relevant knowledge (i.e. the representation scheme) affects the possible solution because every solution must be coded to be learned or stored in long-term memory.[61]

Gestalt psychology suggests that describing design activities using hierarchical organisation according to abstraction is useful because it simplifies the presentation of the data, thus allowing the reader to perceive the situation with its inherent structure. An example of dividing the design system into design disciplines (domains with high levels of aggregation) is given later in Table 5.1 (see Page 96). These disciplines can be divided again into more detailed (and less abstract) domains based on either means-end or whole-part relationships. This 4D model is capable of depicting design activity and the representation schemes used to represent each of the different design domains evolving through it.

As described in Chapter 3, designers focus their attention on different design domains during different episodes in the design process. Rowe (1987) suggests that these design domains expressed in the different episodes, "have consequential connection to each other, which are essential to the closure among episodes and emergence of design proposals."

This consequential connection between design episodes and any design situations does not necessarily involve a one-to-one mapping. Design, as a problem-solving process, requires us to consider all the essential aspects of the problem; the functional relationships between various system elements and processes; the various levels of detail

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[61] This notion was suggested by Vicente (1997), who draws a direct link between expertise and memory coding; this coding mechanism is therefore taken to be part of the expert knowledge and ability.

and abstraction in the design, whether they are physical or procedural;[62] and the various perspectives of examining the design. This variety suggests dividing the problem into a series of workable domains that reflect its sub-problems is useful for configuring and directing the design team.

Now that we understand the concept of design domains, we can examine an additional underling concept of the 4D model. Design activity may be analysed and coded according to design domains and representation schemes (as demonstrated in Chapter 4) to produce a 3 dimensional array, according to the finding of the observation, this array is a comprehensive description of the design activity. Once created, this array may be sorted according to a specific design domain (or a specific representation scheme). The outcome of such a sort would still depict the design activity, since it still contains all the information about the activity. However, once sorted the array actually depicts the chronological development of the specific design domain. This procedure is useful, because it depicts the separate thread of development for the specific design domain, in other words, it traces the development of an individual design domain.

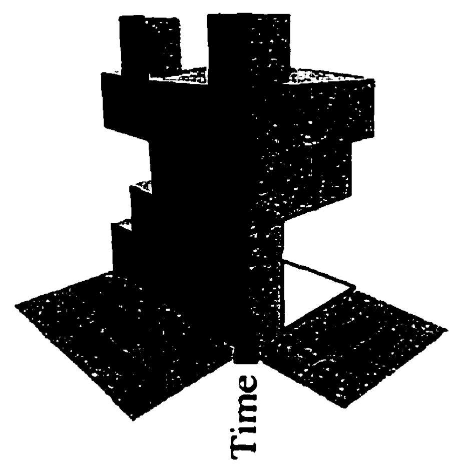

Figure 5.2: A vertical view (time trace), useful for tracing the evolution thread of a specific design concept.

This structure is suggested because it helps to simultaneously trace the evolution of multiple design ideas in the design process. Every particular design domain is shown describes the evolution-thread of multiple design ideas is more complete than other currently available descriptions (e.g. Linkograph), but is also more complex. This method is useful, because it improves the visibility of the various development threads, it allows the reader to follow the process either chronologically or based on design domains. This model allows us to depict design activities composed of multiple domains, which were otherwise difficult to analyse.

Figure 5.2 depicts the evolution of a single domain in the design process; this view depicts the evolution of the individual design issue (idea) from the moment it appears until the end of the process.[63] The continuous evolution of

[62] The physical and procedural structures here relate to the time and space dimensions respectively.

[63] Cross (1997) shows that an idea, component, feature, or concept can be tracked after it appears in the representation, and often before it was recognised by the designers.

ideas in design processes has not previously been examined in such a way, because there was no way of depicting multithreaded design processes in a format where this progression is visible. I also believe that this method of depicting multiple simultaneous sub-processes taking place in most design processes is an invaluable aspect of design problem-solving, and therefore must be a part of describing them.

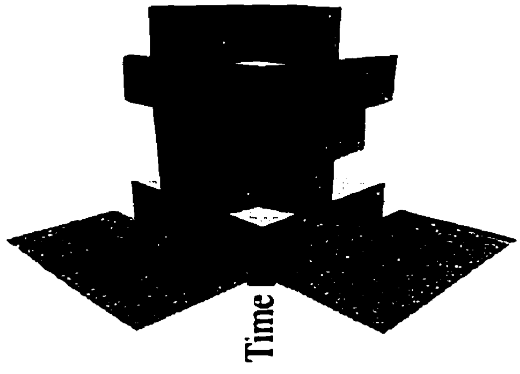

Figure 5.3: A vertical view (in time) depicting the evolution of a single representation (scheme or element) and the design domains is refers to.

Figure 5.3 shoes the 4D model applied to a design process, tracing a single representation scheme (or a single representation-element—when using a high level of detail) and the design domains it was used to represent. This view shows the evolution of the isolated representation throughout the design process.

This view is useful for analysing the role the specific representation plays in the design; it shows when it was used, how, and for what. This is hard to trace in commonly used graphs of design progression, because these graphs do not isolate the representation in a visible way, but rather attach the representations to the timelines where they were created; such timelines that include many jumps between representations.

5.3 The Model Applied to the Design Process

The model divides the design process according to different dimensions, and these are now examined in further detail.

Design Domains: This dimension describes the aspect of the designed product being attended to and corresponds to Schön's terminology of work-domains, as well as to the terminology given by Rasmussen et al. (1994), which state:

> This dimension of the framework serves to delimit the system to be analysed, and thus it represents the landscape within which the work takes place. It serves to make explicit the goals, constraints, and productive resources found in a particular system....(p. 28)

The design domain dimension can be seen as describing the perspective of handling the perceived problem at a specific moment in time. This dimension is important because it describes the specific aspects of the design that are being dealt with, such as anthropometrics, product semantics and aesthetics, or manufacturing constraints. The different design domains are interconnected, because a design move usually has implications beyond the intended or attended domain. Each member (even if there is only a single designer in the team, as in the case reported by Goldschmidt, 1996) of the design team may adopt several domains simultaneously; however, simultaneous domains must be prioritised (Schön, 1983) to help resolve conflicts among them.

Table 5.1: An example of dividing a design problem (a car) into its domains.

Design domains aspect	Divided using whole-part relationship
Aesthetic	Exterior, interior, engine
Structural	Chassis, body/shell, cockpit frame, engine
Physical human factors	Exterior, cockpit, dashboard, engine, trunk
Cognitive human factors	Steering, signalling, accelerating/braking

Table 5.1 shows an example of dividing the design system to highly aggregated design domains. These domains can be divided again, based on either the means-end or whole-part relationship discussed earlier in this chapter, and shows the possibility of analysing the situation data from two distinct perspectives. The example given here is still the design of a car; however, this time the scope is limited to the design of the exterior only. The two perspectives shown are the structural engineering perspective and the perspective of aesthetics in appearance. It is important to notice here that the two problem domains deal with the same portion of the greater design issue (i.e. the car's exterior), yet they have different priorities and different relationships to the data.

Table 5.2: Dividing car exterior design using different aspects.

Aesthetic aspect	Structural engineering aspect
Bumper	Bumper
Wheel caps	—
Windows	Windows
Side view mirrors	—
Roof shape	Roof structure
Door appearance	Door shape, mechanism and structure
Colour coating	Shell treatments and chemical coating
—	Shell thickness and construction

Displaying the domains in car design with one additional level of detail results in a huge increase in complexity as shown in Figure 5.4; the depiction of the entire system is now composed of too many cells, and is complicated to understand.

For this reason, Table 5.2 shows only the car's exterior, as viewed from only two aspects: the aesthetic and the structural engineering aspects.

Representation: The data in design, more than in most other fields, uses multiple representation schemes throughout the process. Each representation scheme is more capable of coding and describing certain things or procedures, while being limited in representing others. A unique quality of design type processes (Goel, 1995) is the ability to use loose, ambiguous representations as an asset and not as a limiting factor. It should be noted that different perspectives of examining the data in different domains result in differences in meanings and data. Each representation scheme is most suitable for certain aspects, components, and perspectives of describing the design situation. Figure 5.4 shows different schemes and the domains they are suitable for.

Design Aspects	Representation Schemes						
	Photographs	CAD Render	Illustrations	2D CAD	Diagrams	Symbols	Verbal
Aesthetic	●		●		○	○	○
Manufacturing	●	●		●	●	○	
Structural		●			●	○	
Marketing	●	●	●				
Anthropometric		●	●	●	●		
User Interaction			●		●	●	●
Environment	●	●		○		○	

Figure 5.4: Suitability of different schemes for representing specific design domains

Figure 5.5 shows an example of the different maps used by city planners to describe the same city; it shows a single location that contains multiple aspects of a built environment such as topographical data, road data, walking paths, bicycle paths, water pipes, and sewage pipes. These multiple representations of the city allow planners to change their aspect and interact with a more specific work domain without the burden loaded by other domains. An important characteristic of design representation schemes is that they rely on perceptual mechanisms for the interpretation of some extended knowledge. This may cause

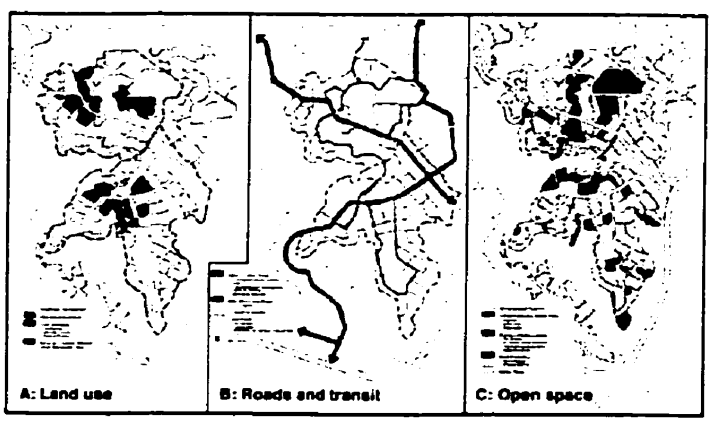

Figure 5.5: An example of a variety of representations of a single situation. Various maps of the same section of a neighbourhood in Calgary, used by urban planners during their design process.

designers to perceive information contained in a representation of one domain as if it belongs to an entirely different domain, leading to an unexpected meaning altogether.[64] This is not yet explained by any known model of representation in design practice.

The concept of using multiple schemes for representing a single item is useful in many cases, because each representation scheme assigns different priorities to the different aspects[65] of the design. Milton Tan (1997) asserts that representation schemes are always restrictive of design transformations, hence alternating between different representations contributes to the creativity of design processes and the richness of their outcomes.

John C. Tang (1989) studied the subject of representation schemes used in design in group settings. He cites Ballay's approach, which suggests that the representation schemes selected during sketching are intentionally ambiguous and imprecise. This ambiguity is used to encourage "inventiveness."[66]

Time: The time axis depicts the time progression during design work or design process. This dimension is the only one that must be represented in a directional way; it is the only dimension in which order and direction are of essence. The time direction (from past to future) is depicted from bottom to top in the graphic model. This direction was selected to depict the nature of human working memory (Wickens, 1992; Miller 1956) so that the perception of data in this model corresponds with the effects of time decay of working memory. (External memory devices used in design work do not, of course, behave according to this model and do not demonstrate this type of decay.) This dimension alone does not show the use of design drawings or sketching; this issue will be resolved later in the discussion of the representation schemes dimension.

Time can easily be represented using a hierarchical structure because it is associated with the time scale spans of years, months, weeks, etc. This hierarchy is useful for scientific measurement scales, but is less useful in describing human behaviour and cognitive processes like design. Instead, I chose a different set of abstraction/aggregation levels in time for analysing and describing design activities.

Different design activities span different ranges of time:

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[64] This unexpected meaning is new, thus, usually related to new (emergent) concepts or features.

[65] An example of using this prioritisation of aspects is aspect-blindness where some meanings (aspects) are not perceived by the reader (Tang, 1990).

[66] The term "inventiveness" used by Tang resembles "emergence" in this thesis.

1) The whole design is evolving during the entire time that is allocated to the project; hence, we name this time scale *project time scale*. This time scale is too large to be useful for analysing design processes, as it is does not have the necessary detail level needed to resolve activities within the project.

2) A smaller unit used for analysing design is a sequence of design moves/events (Goldschmidt, 1989, 1991, 1996; Suwa and Tversky, 1996), and is named *sequence time scale*. The boundaries of this time scale are usually determined by analysing the boundaries of serial sequences of development in the verbal or visual evidence that was recorded. The building blocks of this time scale are individual design moves, and are often represented by single design sketches.

3) The design sketches that compose the sequence time scale are themselves composed of a series of sketch strokes, which can be delimited by the contact periods between the drawing tool and the drawing surface. The sketch elements created during these time scales are used in the graphical description format called "digital ink" commonly used in applications involving hand writing recognition. Each of these elements is defined as a "sketch stroke." This time scale, which uses these strokes as building blocks, is named the *sketch time scale*. I will demonstrate that this time scale is useful in analysing design activities.

4) Each sketch stroke takes time to generate; I name this time scale *stroke time scale*. I believe this time span is not as useful in analysing design because the interactions within this time frame are motor in nature and involve little thinking and processing other than kinaesthetic action control.[67]

The observation described in Chapter 4 demonstrates a procedure for parsing and coding design activities. In that procedure a design move is delineated by the boundary of a verbal design expression. A design (physical) operation needs to be clearly delineated in a similar way. The above description of the different time scales in design activity suggests that a working definition for design operations in this document would be based on paper sketching representation schemes.[68] The design sketching operations are defined as:

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[67] Here, sketching operations are considered to be mainly motor, even though the process of generating sketch strokes is largely based on the perception-action loop, which is discussed in Chapter 3. The reason behind this way of dividing the time scales is that perception-action processes are not usually seen as occurring within known time frames, and do not, therefore, suggest adding additional importance to the stroke time scale.

[68] Design sketches are personal and, change based on the context in which they are used; however, they provide an initial foundation for the definition of the type of representation schemes covered in this paper.

1) A sketching stroke is delimited between pen-down (the instance of the drawing tool touching the drawing surface) and the following pen-up (the drawing tool detaches from the surface).

2) When analysing design sketching operations at a higher level of aggregation, each operation may include several pen strokes used in conjunction for a single purpose e.g. a series of strokes that depict an outline or an exploration of a curve, with a final stroke used to provide a selection of a combined curve.[69]

Abstraction Level: This dimension corresponds to the level of aggregation and abstraction in the described tasks. The abstraction axis divides the problem based on causal and relational connections, and the hierarchy constructed in this paper was found to relate to J. Rasmussen's theory of abstraction hierarchy (Rasmussen, 1983; Rasmussen, Pejtersen, and Goodstein, 1994). The abstraction dimension is not represented as a separate axis of the problem; it is shown as the resolution at which other dimensions are depicted (the resolution of the grid in Figure 5.1). The hierarchical nature of representation schemes corresponds with reviewed theories (Akin, 1987; Goel, 1995; Rowe, 1987) that suggest design knowledge has an inherently hierarchical structure and therefore any representation of it will also be similarly structured.

Using hierarchies to structure representations is common and is used in many applications, such as the feature of Outline-View in MSWord™. This Outline-View allows users to "hide" the detailed text contained "underneath" a heading, making it a useful tool for viewing the structure of a text document. The Outline-View does not use a true abstraction hierarchy, because unlike true hierarchical structure of representation scheme, corresponding with the reviewed theories (Akin, 1987; Goel, 1995; Rowe, 1992), the Outline-View hides detail only based on format and not based on true knowledge inherent to the content of the document.

In MSWord™, users artificially define the hierarchy by formatting different text styles. The created format is constructed independently from the content and may therefore be completely mistaken. For example, a chapter including the occurrences in Tuesday may be under the Thursday heading. This example demonstrates the strength of using hierarchy based on abstraction in its simple form, one that depicts higher levels of aggregation without increasing the level of abstraction. The idea behind this strategy is that human cognition was adapted to operating in complex environments by representing large amounts of knowledge as meaningful clusters (known as chunks), to make our interaction with the environment more simple and "automatic." The abstraction hierarchy

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[69] This described series of operations is a common procedure in design sketching described in Chapter 4 under the Renaissance term *pentimenti*.

is a modular system of representing and interacting with the world, i.e. it can be used to save resources in solving problems by recognising familiar modules and acting effectively in incomplete or unanticipated situations as reported by Vicente (1992, 1997).

5.3.1 Structure in Design

The previous section described the four dimensions of the proposed model, and the benefits of using hierarchical structure for depicting design activity. Analysing and depicting design activity are difficult because much of the design process takes place inside the designer's mind unseen by the rest of the world. This means that design activities can only be studied indirectly by carefully recording and examining the external/visible by-products produced during design work. The following section describes the structure in design activity.

The 4D model suggests a structure for the design process, its correlation to the product being designed, and the representations (e.g. design sketches) produced during the design process.

Ivan Sutherland (1973, p. 75) states that sketches are not structured, and as such are "mere dirt marks on paper," but because he studies the subject from a computer-graphics perspective, all he is willing to accept are mathematical structures. But what about other types of structures? The theoretical foundation behind the 4D model is based on perceptual mechanisms and the actions they afford; this allows for non-mathematical structures, such as grouping combinations and exceptions described in Gestalt psychology, which result in the two dialectics of sketching suggested by Goldschmidt (1991). Such structures exist in sketches when they are seen in respect to the design process of their creation. For example, representations of a given physical component from different aspects and perspectives will display some similarity (see Figure 5.5) and structure, even though this structure may only be apparent at high levels of abstraction; detecting and understanding this structure may require some extended knowledge (see Chapter 3).

We should return to Donald Schön's comment (1984, p. 78) on the design process: "often...he [the designer] makes a representation—a plan, program, or image—of an artefact to be constructed by others." This comment increases the importance of design representations by stating that designers often produce only a representation of the object they are developing. Here, representing the product is seen as the operative goal, which then suggests that examining by-products of design (the design sketches) could result in a productive reflection of the design process.

The notion described in this section is based on the common understanding (Goel, 1995; Goldschimdt 1991, 1992; Rowe, 1987; and others) that design sketching can be seen as analogous to design thinking, and can therefore be used to understand and describe design processes. The 4D model suggests that understanding the structures that make sketching useful for supporting creative design may possibly be used in, and help to improve other design aids.

5.3.2 Operations in the Design Process

This section describes design operations, which are the basic building blocks of design activity. The four dimensions discussed above yield the following definition for design operations:

1) The concept of hierarchy in the 4D model requires our definition for design operation to comply with this hierarchical structure, i.e. design operations can describe various levels of abstraction and detail of design practice. For example, describing appearance of an object may include descriptions of colour, 2D shapes, and 3D curvatures.

2) The dimensions of the representation scheme indirectly determine the type of possible operations. The operations defined in design using a CAD tool suggest that the operations correlate with the operations provided in the tool's interface (rotate, move, copy, etc.), but in 3D clay sketch modelling, the operations are defined as lump, smear, push, pull, or squeeze. It is difficult to draw parallels between specific operations in different representation schemes, such as CAD example given above, and impossible when the representation schemes cannot be modified (such as clay modelling, using mechanical components, and feasibility modelling). For further detail on the transformations in design representations and their associated operations see Tan (1990, 1997).

3) The dimension of a design domain influences the definition of design operation, because the repertoire of operations in structural engineering in car design is utterly different from the repertoire of user-interaction design in the interior of the same car. This results in differences we cannot bridge in the definitions of design operation under the various domains.

4) Time seems like the most natural dimension for defining design operations, but it should not be the only dimension used. Because as shown in chapters 3 and 4, design activity tends to make concurrent advancements in different portions of the design problem and the designed entity by jumping between these portions during different design episodes.

After relating the 4D model to design operations in design activity, we can continue and propose ways of utilising the model. The following section suggests how the model could be used for analysing, describing, and guiding design activity.

5.4 Using the 4D Model

The proposed model could be used to describe and design processes. The 4D model describes the design progression as a series of layers, each representing a consecutive design situation. Each of these layers (Figure 5.6) is a 2D view of the design representations and design domains at a given point in time. The 2D horizontal slabs in the model describe the design situations and reflect the evolving structure of the product, the perceived design situation, and the way it is being represented at each point in time. This view is useful in order to analyse correlation between the representation scheme used and the design domains it comes to represent. It is important to note that representations in the design accumulate over time and exist even after the design attention is shifted to other issues. The model solves this problem in a unique way. Instead of displaying the whole multitude of representations visible at each instance, each layer shows only the representations and domains attended to at that time. The entire accumulation of information is visible when assigning appropriate[70] transparency to the layers in the model and viewing it from the top. This view (with transparency) allows one to see the accumulation of representations and design domains.

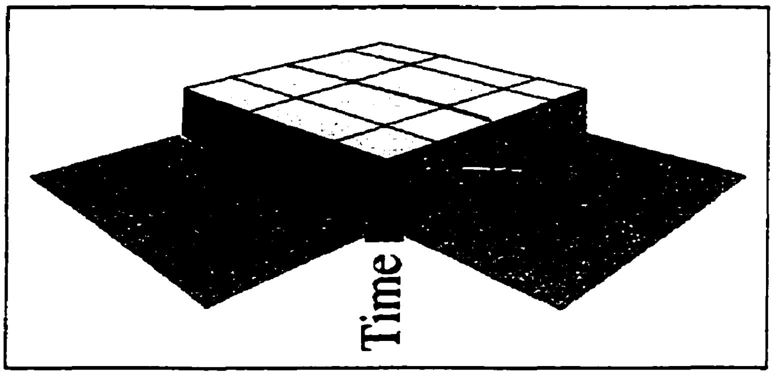

Figure 5.6: A diagram showing the horizontal coding of a single design situation—without time progression.

A selection of a view along each of the three planes composing this model must be done along with specifying the required (or desired) level of detail corresponding with the level of aggregation of abstraction needed. For example, when analysing a single curve in the design of a door handle, one must consider working with a high level of detail and a low level of abstraction. If this is not done, one would be forced to see a large number of details that would obscure the view of the desired detail when selecting a lower than necessary level of aggregation or have too few details and too much abstraction; not enough to observe the desired design element when selecting a higher than necessary level of abstraction. The results of using such traces in time are shown is Figures 5.2 and 5.3.

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[70] The transparency appropriate for each layer is based on the time elapsed from the time it was active. This value was chosen in order to represent the time decay in working memory, which effects the availability of the information to the designer. For example, revisiting representations and domains increases their appearance through the top layer, which represents how their weight in working memory would be affected.

The model is also useful for analysing the development of single elements in the design, such as a specific feature or component. This can be done by isolating the development thread representing that specific design domain (Figure 5.2), as this view is depicts all the chronological changes made to this design element, component, or aspect as considered from a specific perspective. In other words, a view depicting the evolution of the element through the design activity.

The model could be used to track the evolution of specific representation items (or set of items considered as a single element) through the design activity. Isolating the instances related to a specific representation element would yield a set that contains only the instances where the designer used or focused on that element. In other words, it corresponds to the chronological thread of using the specific representation element during the given design activity. An array of these isolated instances in time (Figure 5.3) would therefore depict all the chronological states of that representation element throughout the design activity. Figure 5.3 schematically shows an example of such an array where time (in the activity) is depicted as upward along the vertical axis. Such an array would be useful when trying to evaluate the changes in syntax or semantics in selected design representations. These arrays deliver on Rowe's (1987) suggestion that tracing the focus of attention (design domain) found during design episodes can show progression of ideas. As he suggests, the resulting picture may not be linear, although the 4D model allows us to track these progressions even if they are multithreaded.

5.4.1 Design Problems and Processes

The design problem in industrial design is to define and describe (i.e. represent and communicate) a product that satisfies the specified goal under the given constraints.

Design problems can often be classified as wicked problems. This suggests that they could be analysed through a blend of different perspectives yielding different sets of design components and aspects. Each of these blends may result in different solutions according to the priorities assigned to the different design considerations. I propose a way to analyse design problems by using a combination of the different ways of formulating them. Different design solutions are based on different combinations of objectives. There is no guarantee that each objective will correspond with a single design variable. In fact, the connection between goals and solutions is much more complicated. It seems that each single solution, in most cases, involves a combination of all the possible design variables.

The way to solve this problem is to isolate each of the objectives and analyse their relationship to all of the design variables, or evaluate each design variable and its effects on each of the design objectives. The problem here is threefold: 1) The design goals and their priority often change during the different episodes in design activity. 2) There is no way to completely isolate a single design goal and design towards achieving it without affecting the results or scores of other goals. 3) How can designers represent the necessary information without duplication.

The solution to these problems seems to be the way many designers practice design: the recognised problem is broken into its sub-problems, the goals are broken into sub-goals, and some initial relationships between them are formulated as much as seems possible without committing to a specific solution. In addition, designers tend to represent variability and dependency among design variables.

This initial state of the design problem is represented as the base layer of the proposed model. The different parts and aspects of the design problem determine the listed design domains, and then a variety of possible representation schemes related to this former list is found. At this point, the designer selects a set of representation schemes and uses them to represent selected design domains.

An important issue is to maintain the flexibility of this representation by using representation schemes that can contain large, loose, or vague, as well as ambiguous and ambivalent, representations.

Based on the finding of the observation described in Chapter 4, I argue that this structure can represent practically all the knowledge required for defining and representing the designed product. The first argument is that the motivation of creating the model and the definition of design domains was based on the common notion that design activity can be described by decomposing it according to the components of the evolving design entity (Goel's "design modules"), the aspects of the design entity's functionality (Rasmussen's "problem domains"), and the various design perspectives (Schön's "work domains"). The second argument is that each piece of information used during a specific design activity would have to be represented and eventually communicated to a certain part of the design team.[71] Each part of the design team is usually given the mandate to resolve certain aspects and parts of the design problem. Each representation scheme (defined according to the communication channel used by that team element) must therefore be covered at least once, when the relevant knowledge is represented and/or communicated.

The reasons for using the design methodology described in the model are rooted in the limitations of human cognition. It is commonly accepted (Finke et al., 1992; Klein and

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[71] The reader should remember that design roles are assumed by one or more designers (or design-team members) and, therefore, a design-role is not identical to a specific designer. This is clearly demonstrated in the observation, where the participant assumes different roles during the session. This is the reason for referring to part of the design team rather than a designer.

Crandell, 1995) that experts interact with the world by using a variety of mental models, each of which represent a certain portion of the world's behaviour from a given perspective. Rowe (1987) notes that designers interact with the design situation using different mental models and different sets of heuristics during different design episodes. A useful model is effective because it allows designers to reduce the complexity of the problem by interacting with a specific design domain. This isolates and concentrates on specific aspects, prioritises and organises different elements, and interacts at a higher level of abstraction that also contains less detail. Vicente (1997) suggests that the use of hierarchically structured mental models can also improve the efficiency of memory storage and recall in expert behaviour.

Applying the model to the activity after it is applied to the product is suggested because the design domains results from analysing the product can help to construct similar processes in the future. Using the model to describe the process yields a description of past occurrences, and more importantly, a direct link to the ongoing design process by keeping an organised map of it. It is important to remember that design problems—as ill-structured ones—cannot be fully described *a priori*, which suggests that the design domains and the perceived definition of the design problem evolve throughout the process, and the model depicts this evolution as a series of design situations shown as 2D horizontal slabs.

Following Goel (1995), Rasmussen (et al. 1994), Schön (1983) design domains described in the proposed model are said to be internally represented by a corresponding mental model, which makes concentrating on them very efficient. Based on the discussions given by Klein and Crandell (1995) and the examples found in the observation, it is stated that the apparent limitations of using a mental model are:

1) the expert interacts with a model, which is different from the real world;

2) portions of a (design) situation are disregarded, as they are either hidden (embedded or removed in the model) from the user, and

3) the perspective of interaction is biased and distorted, and the order of priorities is shuffled.

Using a single design domain is therefore not a sufficient solution; however, a balanced selection of design domains can reduce the first limitation, while adding other design domain can significantly reduce the second and third limitations.

It is important to note that designers often employ more than a single design domain during the process of solving a specific problem. For example, in session 3 (time code 1:14:24), Participant C examines the problem of attaching the wearable computer to the users' waist by means of a strap. He then uses the design domain of a belt, and represents this model by stating that it needs some sort of "strapping," sketches the strap, refers to it as a belt, and finally adds a buckle. This model allows him to concentrate on the problem of "buckling" rather then having to deal with the entire problem of attaching the device on the body. The selected solution is a very specific type of belt-buckle ("a low-profile buckle," which is "tucked in flush" into the face enclosure of the device without an additional part.) Here, the designer shifts from a design domain of strapping that is more technical to a "cowboy" belt system and then finishes by combining the two into a high-tech belt system where the device's enclosure serves as the "cowboy buckle." The scheme used represent this design domain allows the designer to switch to a different part of the design and return to the strapping-connecting problem without any difficulties. It seems the information about the belt system was recalled very efficiently.

Rowe (1987) doesn't provide a complete explanation of the reasons for shifting between episodes. However, he does suggest that changes are often visible in the behaviour during different episodes. Based on the following examples found during the observation, I suggest that the transition between different mental models may occur in the transition between consecutive design episodes under the following situations:

1) The design process has reached a situation in which that design domain no longer applies, or another design domain exists that is more appropriate for the new situation. For example, at time=1:30:33, participant C is no longer dealing with the wiring-path design aspect. At this point he switches to " go[ing] back and look[ing] at [another element.]" The mental model used to analyse the wiring solution does not apply to physical shapes and symmetry (which is the aspect used then).

2) The designer is no longer satisfied with the progress in the process or the route it is taking. For example, at time=1:28:21, participant C testifies that he "doesn't have a clue what he is doing" and switches to a different design component, where a "nose bridge" is used as a metaphor.

3) A change in the design situation causes changes in priority or approach. For example, at time=1:26:59, participant C switches from dealing with the design from the aspect of attaching the goggles to the body, to the aspect of user behaviour. He moves from high priority assigned to one component to temporarily assigning higher priority to the standards of usage.

4) A switch between design domains is initiated methodically. The methodical switch is suggested in order to ensure a balance in dealing with the variety of domains. For example, at time=1:19:32, participant C decides to end the episode of designing the buckle, when he says, "OK, so ...now the goggles..."

5.4.2 Creativity

To evaluate the efficiency of the proposed model for exploring creativity, it is compared to existing models proposed by Gero and Rosenman (1993) and by Cross (1997).

Gero and Rosenman use four generic principles to describe creativity in design. To show the correlation between the model proposed here and that proposed by Gero and Rosenman, each procedure is described in terms of my proposed model and supported by concrete examples from the conducted observation (where available).

Combination: This procedure is described as combining different features or details from two or more elements, leading to a new idea. In terms of the 4D model, combination involves a shift down in abstraction level (from considering the different elements to considering their features or details), then a shift in design domain (to select the proper details or features according to a new approach or aspect), and finally up in abstraction level (from details to considering the whole element).

Mutation: This procedure usually involves a shift in representation scheme or in design domain. For example, starting with "I'll have a strap going off" (the abstraction level is strapping-system elements-strap, and the design domain is shape), moving to "that object (the strap) will take off, whatever buckle type" (the abstraction level is strapping-system-elements-belt, and the design domain is shape) indicates a shift in abstraction level between two elements of the same system.

Analogy: This procedure is usually a shift between design domains using a symbol, an icon or a model representing the situation as a metaphor. For example, in the observation, Participant C uses the analogy of a belt to design the strapping system that connects the hard drive system to the waist.

First Principles: This procedure involves generating a new concept without any connection to previous actions. This type of occurrence cannot be described in the 4D model because this model is based on changes between two stages, where the first one initiated the second. In First Principles, the initiating state is not shown in the protocol, and therefore cannot be considered for analysis in the model.

The 4D model displays a considerable ability to explain emergent cases shown using other models. The advantage over other models is that the 4D model displays the characteristics of the representation schemes involved in the process and can suggest ways of creating such representation schemes for working in computerised environments and shows development threads of specific components, aspects, and perspectives during the design activity.

The previous sections considered only examples from the conducted observation, let us now apply the 4D model to examples from other sources. The following section analyses examples found in related literature.

In Cross (1997), designers consider the idea of a "bag," then combine it with the idea of a "flat panel" yielding a new idea of a tray (see Figure 5.7). In terms of the 4D model, we see that the "bag" was considered as a soft enclosure which can contain objects (DD= structure-parts-intended role; RS= verbal, appearance schema; AL= the whole bag) => vacuum-formed tray (DD= manufacturing-form, RS= professional terminology, shapes which fit the manufacturing process, AL= form details guided by a manufacturing process).

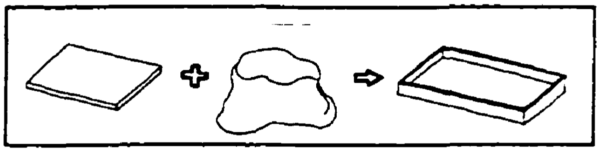

Figure 5.7: The emergence of a new concept by combination (Cross, 1997).

Here we see a shift in representation scheme from an icon describing the appearance of an object to a scheme representing the details of the shape as guided by the common understanding of manufacturing process in the group. There is a transition between the entire object to the functionality of its details, and from there to a new object with related functional-features (walls that provide the ability to contain objects). Later in the protocol, we see a shift in design domain from "this (backpack) frame outline" (DD= structure-composition) to "you can vacuum-form a tray" (DD= manufacturing- shapes) to "... a small part of a tray" (AL= from the whole tray to its parts) to "something to dress this (straps)" (DD= components-function) to "maybe the tray could have plastic snap features in it" (DD= components-manufacturing => manufacturing-shape-features, RS= form described by plastic manufacturing guidelines) to "so you just like snap your backpack down" (DD= shape-function, AL= features => whole backpack).

This section demonstrates how the model could be used to describe creative instances. The advantage it has over the theory proposed by Cross (1997) is that in addition to detecting and describing the new ideas, this model also provides some information on the representation scheme used in the process. The disadvantage of the theory proposed here is that it does not directly explain how and why the shifts result in creativity.

5.5 The Industrial Design Process

The model introduced in this chapter can be used to describe—or as will be described later, used to direct—systematic design processes.[72] The model is based on describing design situations composed of design domains (i.e. design issues), the schemes used to represent them, and the operations used to create, modify, and move among them. The model is a method of describing the structure[73] of design processes in multiple layers, where each layer corresponds to a level of abstraction and aggregation. This method of dividing the process into layers by levels of aggregation is adapted from Rasmussen (1983; Rasmussen and Vicente, 1991; Rasmussen et al., 1994). The reason for using an abstraction hierarchy here is to show the design process using a tree structure, which allows the viewers to select levels of detail they choose in order to view the entire process or parts of it in greater detail. Building this hierarchical tree structure requires a theoretical background understanding of the design practice, because any organisation of information in such a structure encapsulates additional information and understanding of the field at hand. Unfortunately, such theoretical background is still unavailable on the field of design. An additional problem in constructing such a model of design practice is the necessity to derive the understanding of cognitive processes in design from the analysis of visible actions and tangible objects. Design researchers tend to use protocol analysis in order to analyse design activities because it provides them with verbal testimonies given by the designer, which can arguably (Ericsson and Simon, 1987) reflect the cognitive processes which take place in the designers' mind.

Lawson (1990) argues that designers construct their design methodology "on the fly" and do not rely on any prescribed process for their designing. Furthermore, he argues that designers are not even able to follow a given design map due to the complexity of the design task. My understanding is that designers indeed use their own personal interpretation of a known design methodology and continuously adapt this methodology to accommodate for the specific needs of the current design situation. This approach complies with Schön's (1983) notion of reflection-in-action mentioned earlier in this work.

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[72] The term systematic design process refers to the approach of planning design practice according to the specific details of the initial design situation. This approach is described in detail in Rouse et al. (1987).

[73] This chapter describes design as a structured process, in contrast to the previous sections that show that this is rare. There is no point in discussing random or completely ill-structured processes, because they do not serve any practical purpose, whereas partially structured processes—common in industrial design and engineering—contain many similarities to allow for a more productive study.

Goldschmidt (1996) postulates that industrial design lies between engineering and artistic design disciplines. This suggests that a systematic description of the industrial design process is limited to cases where a structure exists. A recent study conducted in the United Kingdom (Fisher, 1995) suggests that the breed of "designers as artists" (designers that practice design as artists and not as a profession influenced by real-world constraints) is indeed disappearing and is common only among design educators.

More structured disciplines involve more constrained design (such as industrial design engineering) than artistic design and contain fewer capricious and non-systematic activities. This thesis complies with that notion and does not extend beyond the boundaries of systematic design. However, I hope that the model will be useful to all design disciplines by offering a description of the more systematic domains within these rather artistic design practices.

Describing the design process at this level of detail can result in an overwhelming number of process elements (operations and links). I concentrate on describing *operations* rather than whole *activities* by describing the operations and not necessarily the links between them, yet maintaining the context in which they appear.

This model should help visualise the connection between design problems, design processes, and design activities—the actual serial procedures found in empirical observations of design problem-solving (Dorst and Christiansen, 1996; Goldschmidt, 1991, 1992, 1996; Suwa and Tversky, 1996). The biggest difficulty in achieving this goal is representing the occurrences in the multidimensional problem space of design (Goel, 1995) in a way that conveys the multiple concurrent processes that form part of the design process. The 4D model resolves this difficulty by allowing us to isolate the development threads associated with a specific portion or aspect of the design-entity. An added benefit is the model's ability to isolate the evolution threads of specific representation-elements, which can be used to understand the effectiveness of each scheme in representing design situations along these development-threads.

The process of solving design problems requires attention to many aspects of the problem: each aspect can be composed of sub-problems and may require different perspectives and knowledge. Human cognitive resources (i.e. memory, attention, etc.) are limited; hence, parallel-processing capability is limited.

The common solutions used by designers to solve complex, multidimensional problems are threefold:

1) Designers often work in teams (Cross et al. 1996), where each design team is composed of various experts. These experts possess a variety of perspectives so that the team as a whole covers the entire range of different requirements for knowledge and understanding. Separate perspectives are divided among actual

people or simulated by experts playing a "role" of another team member. This means that a single designer can assume multiple expert roles by viewing the problem from the various perspectives.

2) The responsibilities of each team member often include multiple problem domains (e.g. Cross et al. 1996). Designers deal with all these domains by dividing their attention among them over time (i.e. time-sharing).

3) Design tasks are performed using different levels of detail and abstraction, thus reducing the load by reducing the amount of detail processed (Rasmussen et al. 1994).

Applying these three solutions yields a method for structuring design around the available resources.

5.6 Conclusion

This chapter demonstrates how the 4D model can be used to study, describe, and direct design activities and the schemes capable of representing the information used in them.

The model introduced in this chapter describes design according to four dimensions: design domains, representation schemes, abstraction levels, and time. It is based on the understanding that even though design is not well-structured, it can still be—at least partially—structured according to functional and whole-part decompositions and perspectives. Understanding the human behaviour in design, as apparent in this model is founded in the model of recognition-primed behaviour (Klein and Crandell, 1995), along with the structure and usage of design knowledge as they are used in design problem-solving practices. Furthermore, it is suggested that sorting design elements according to the perspective that designers use to interact with them is useful because each of these perspectives has its own unique mindset that determines the mental models designers use. The primary dimension in the 4D model is design domain; this dimension is unique in that it incorporates decomposition of the design problem, the designed entity, and the design perspectives used during the design activity.

The model was originally constructed in an attempt to sort data collected in the observation. However, the findings from Chapter 4 suggested that the four dimensions might be capable of depicting design activity with the added benefit of showing isolated development-threads and the chronological view of interactions with specific representation elements. As shown in Chapter 4, designers display episodic characteristics in their behaviour. They tend to jump from one design issue to another, shifting their attention from one design aspect of a given design component to another aspect of that component or to the same aspect for a different component. The 4D model is seen as providing more understanding of the episodic design behaviour described by Rowe (1987).

The model is also based on decomposing design according to whole-part and means-ends relationships. This method was previously suggested by Rassmusen et al. (1994), who shows that it is useful for structuring goal-directed activities. Structuring the design process in the model is based on grouping and linking related situations according to the above mentioned relationships. Goldschmidt also uses links to show structure in the process; however, she determines links only by analysing verbal testimonies. It is interesting to note that Goldschmidt's Linkograph may seem to show hierarchical structure, which is an illusion. Linkograph is essentially two-dimensional (time and links), whereas the model described in this chapter is four-dimensional. Linkograph depicts the links between each pair of moves, whereas the 4D model depicts the chronological sequence of design moves (development-thread) related to the specific element, aspect, or a consideration from a similar design perspective.

Allen suggests considering design as a situated activity. The 4D model does in that each element is considered in the context of all four dimensions, including the perspective or approach used at the time.

The 4D model is capable of describing emergence of new ideas, and unlike the theory described by Cross (1997), it describes the settings around the emergence of these new ideas. Unfortunately, it is unable to explain the reasons for its emergence.

The model is suggested as a method for analysing design activity in accordance with the representations used in it. It is a method for describing the settings found in close proximity to emergent instances, and as such, is seen as a tool for constructing design tools that can support creative design exploration.

6. Conclusions

This study describes the role design sketches play in the design practice. It suggests that design sketches are used as a form of storing and communicating design knowledge and intentions, as well as serving as an external memory aid. It is recognised that design sketches are one of the few representation schemes that allows designers to represent information in a vague, loose, incomplete, multiple, and incongruent fashion; all these characteristics of design sketches contribute to their effectiveness for supporting design practice. The concept of extended knowledge is useful in explaining how sketches are used to encode design knowledge, because it shows that parts of the representation contains knowledge indirectly. This extended knowledge is then interpreted by the viewer within the viewing context, and is often different than the context of generating the sketch. This portion of the representation allows designers to switch between different semantic possibilities and create new and unexpected ideas.

The analysis of the observation conducted in this project also explored the emergence of new ideas in design practice. These emergent instances were found to be in close proximity to jumps between and within different design domains, among different representation schemes, and among different levels of abstraction and detail. This finding is important because it suggests that any tool that is intended for supporting creative design should support these jumps.

An additional finding in the observation was that designers use a unique type of sketching called *oversketching*. In oversketching, designers sketch over existing sketches and usually make only minor changes in these sketches. Oversketching is interesting because it requires very little attention from the designers, and they seem to be able to use it to help them perceive the sketch and the design situation it comes to represent. Oversketching is not possible in computerised environments, because it requires the designers to directly interact with the sketch and computer tools require designers to translate their action and formulate them into non-human language. This translation requires attention and time, breaking the perception action cycle used in oversketching.

The observation showed that designers rely on the use of various levels of privacy in language, use personal language to quickly and efficiently represent their design thoughts, and use more public languages to represent information that they intend to communicate with others. It became apparent in the observation, reported in Chapter 4, that designers often refer to sketch elements and associate meanings understood only to them, for example, at time=1:29:06, Participant C sketches an oval shape and states: "I'm not gonna draw a head ... forget it! Imagine there's a head there." Here, an oval doodle is used to represent a human head; this representation is private and may be understood by others only after an additional description is given. This is an example of the notion of extended knowledge suggested in Chapter 3.

This is important because it suggests that a CAD system will be a limiting factor to efficient representations using these languages, and that the computerised tool will have to understand the language in order to facilitate an efficient use. For example, when a sketch element refers to an outline, it can be filled with colour, but when a similarly looking sketch element refers to a texture, it is used to fill other outlines; this will require the computerised system to offer different sets of tools for such cases.

6.1 The Theoretical Model

Describing the design process is difficult because it involves multiple dimensions in the design problem-space. As a result, each designer may use various professional approaches to solve the design problem. This thesis uses theoretical foundations established by D. Schön that describe design as a process of reflection-in-action in which designers perceive the design situation and navigate through the problem space using their experience and expertise.

The idea of shifts along the four dimensions of the model emerged based on examination of results in the observation in Chapter 4, but also connects nicely to theories of Cross (1997) and Goldschmidt (1991, 1992).

The model resulting from my investigation depicts the design situation in a 4D space with the following axes:

1) Time: the actual time in the process

2) Design domains: the various aspects of the design situation, and the different perspectives of interacting with them.

3) Representation scheme: the various methods of representing and conveying situation and the possible solutions.

4) Abstraction level: the level of aggregation that correlates with the level of abstraction in interacting with the problem, the situation and the suggested solutions. This axis complies with structures found in human cognitive processes. (Akin, 1987; Goel, 1995; Simon, 1969; Rowe, 1987, Vicente, 1997; and others) Therefore, using this axis to describe design offers a more organised understanding of the design situation.

As mentioned, the 4D model that emerged from combining reviewed theories with the analysis of the observation provides a way of depicting design processes in accordance with the design problem they come to resolve.

Goldschmidt suggests that designers use two distinct ways of seeing: *seeing that,* where designers interpret data directly; and *seeing as,* where designers apply Gestalt consideration to the information. "Seeing as" is unique because it allows designers to process a piece of information and transform it or the way of looking at it. The most basic Gestalt process is grouping, which transforms a set of elements into a single element; this process describes a shift in abstraction level in the 4D model.

Another type of "seeing as" is assigning a "role" to an element, i.e. the interior space is seen as a corridor, and its main role becomes to facilitate traffic from one room to another. This is similar to a shift in design domain in the 4D model, where the functionality or the perspective of considering an object is changed.

The model is useful for showing a way of applying structure to design practice by using evolving structures in their design problems, and as such, can serve as a tool for planning design actions; depicting threads of evolution of individual aspects, components, or representation elements in design practice, which is useful for studying creative cognitive processes in design, and by providing descriptions of the schemes used for representing design situations, which can help develop design representation schemes suitable for facilitating creative exploration, both in traditional and computerised environments.

The three main tasks proposed for the model are:

1) Describe design progression, which includes the evolving definition of design problems, and design processes.

2) Serve as a tool for planning design practice. The method of creating the set of design domains and the selection of the schemes most suitable for representing them thereafter is useful for both traditional and computerised tools. This method provides designers with a means of dividing their resources among the different design issues they will be facing in the process and also the different schemes that will help them in encoding the relevant information.

3) Serve as a tool for analysing design activity. The model can be used to trace and depict the evolution and interactions with various elements in the process. This is useful when designers wish to extrapolate or interpolate a given line of development; or when a team of designers wish to analyse the use of a given representation scheme or method.

6.2 Additional Findings

6.2.1 Extended Knowledge In Design Sketching

In review of the theories of design, it became apparent that a unique characteristic of design representation schemes is the need to maintain a controlled level of vagueness throughout the process. Simon suggests that a representation can be in an *extended knowledge state*, defined as knowledge that requires additional processing, in order to be expressed. I modify Simon's term and use the new term *extended knowledge* to refer to the portion of information that is not fully expressed in the existing representation. An interesting problem appears when using this term; it cannot be represented in current computerised representation schemes, because those require a complete expression of the data.

It appears that extended knowledge is important for creative processes, because it allows for multiple meanings within the representation, thus offering different ways of diverging from the pre-selected option.

Extended knowledge allows for changes in meaning through iterative cycles, because it may be context-sensitive; context often changes between consecutive iterations in design, and can define the direction of progress in the design process, because in successful cases of design processes, such processes move from large amounts of extended knowledge to smaller amounts of it.

Extended knowledge appears to be an important variable of design representation schemes and should be facilitated in CAD tools including the more specialised CAID tools.

6.2.2 Oversketching

During the observation, it was found that designers often sketch over existing sketches, and the results of this action often leads to an improvement or an emergence of new concepts, features, or ideas; this procedure was called *oversketching*. The unique aspect of oversketching is that designers seem to be able to oversketch with little or no noticeable effort[74] in either sketching or other simultaneous operations. Yet the oversketching operation itself seemed to point to an increase in focus of attention followed by an improvement in the design, although none of these aspects was quantitatively measurable under the experimental settings.

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[74] The lack of effort was evident in the fact that no reduction in performance was detected during oversketching This performance was expected, because of the addition of another task and no addition of resources (such as attention or amount of working memory).

The proposed explanations to the phenomenon are:

1) As designers engage in semantic interpretation of design sketches, they are required to interpret portions of extended knowledge. During this process, they explore different meanings and oversketching is used to store these different options and to navigate through the web of options (in Schön's terminology).

2) Designers use oversketching as an active part of seeing (in Hill's terminology) as they feel the sketch as they trace the various details, components, and perspectives in it. For example, when participant C sketches over the outline of the main component, he seems to experience each of its curves; he seems to "clean" and crystallise the shape so that it looks much more defined, precise, and accurate.

Oversketching is a part of seeing, and seems effortless even though it often helps designers focus and improves efficiency.

6.3 Implications on the Development of CAD tools

The results of this project suggest that a CAD system should support design practice through all phases of the process, and such a system may be composed of a single tool or from several tools tightly integrated. The integration between the separate components should not impose additional tasks on the designer, and the transition between these components should be allowed to occur at all times and in all directions. For example, designers should be allowed to move from a 2D sketching module to a 3D visualisation module and back with no effort. The transition between different modules should not limit the interaction with the representations of the design situation. When generating a shape, all modules should allow smooth transitions between texture descriptions to 3D curvature and back to texture detail.

An efficient CAD system should support creativity by allowing designers to create, modify, and interact with design representations at various level of detail and aggregation. There should be means of controlling the relationship between the level of aggregation, the level of abstraction in the representation, and the process of interaction. For example, displaying an entire model of a product does not require showing details; when displaying a section of a building at 1:500 scale, one usually wants to see wall thickness, not information about screws and their threads. This quality affects efficiency, because it allows designers to create and modify designs without the tedious task of interacting with all their details. This can only be done by relying on the extended knowledge in the representation of the design situation. For example, knowing how much detail of the section to be displayed can be determined by knowing how much detail is usually required in such representations, or by asking the constructor what he or she would need. This requirement was seen in the observation: at time=1:29:06, Participant C represents a human head by drawing an oval shape and stating "I'm not gonna draw a head ... forget it! imagine there's a head there."

CAD systems should allow designers to interact with design information from different perspectives. The interaction with the design knowledge changes when the perspective is changed. For example, a sketch at time=9:49, a sketch element is used to represent a shape of an object and its fit to the human body, and then at time=10:39, the same sketch element with addition of a single stroke, is used to represent systems components like the battery.

In addition, CAD systems should allow designers to isolate and interact with different components of the design; the separation into components should be tailored to the inherent structure of the design situation, but the freedom to separate the design arbitrarily should also be allowed. This is important because designers seem to shift their attention between design components and these jumps between components are related to creativity. It is important or note that the separation into components can be done in many ways, but the systematic approach suggests using functional and whole-part decomposition.

This section suggests some recommendation for the development of CAD systems in general, whereas the following section refers specifically to CAID.

6.4 Directions for CAID Development

A CAID system should be supporting designers in achieving the goal of designing objects from start to finish, from all possible aspects of design without limiting it. CAID tools should preferably improve the efficiency of the design process by increasing quality or quantity (speed) of designing.

I suggest that a CAID tool should be different from a generic CAD tool as follows:

1) It should fit the unique products involved in industrial design, as products in industrial design are smaller than in architectural design or urban planning.

2) It should facilitate communications with the particular audiences in industrial design and should allow for representing tool makers' language and symbols, because they are different than the language of building constructors.

3) It should facilitate all different domains of industrial design by displaying designs according to geometric grouping, cost, ease of use, etc.

4) It should allow all possible representations of a design, including from shape-manufacturing considerations, from structural-engineering considerations, and by

representing visual appearance, stress-analysis, or intended market segmentation (Potter, 1995).

5) It should be able to facilitate the different levels of vagueness-accuracy and use of private language, needed throughout the design process and allow for loose schematic drawings as well as accurate production models. This project suggests that the only way to achieve this is by integrating extended knowledge to the accurate and precise representations existing in today's CAD.

6) It should allow designers to use representations that closely resemble natural representations; this resemblance should include both the coding schemes and the interaction with them.

6.5 Requirements from a Design Representation Scheme

In order to be useful for design, I suggest that a representation scheme be able to display the following:

1) The wide variety of shapes used in the various design fields (Potter, 1995).

2) The range of processes and transformations, and the possible states existing in them (Potter, 1995).

3) The different flow elements (e.g. information, material, energy) in the various processes.

4) The relationships between different elements in the design, including whole-part and means-end relationships (e.g. the relationships between a mechanism and the object it acts upon).

5) The behaviour of the system, its sub-systems, and elements (i.e. actions and reactions in the system).

6) The feelings and emotions in the process and the design.

7) The environments (e.g. cultural and physical) in which the design is developed and used.

8) The image and styles of the design.

In addition to these requirements, it is useful to request two more requirements from the ideal scheme: it should be fast and efficient to use.

Any such representation scheme should also allow for representing these aspects with maximum flexibility; representing the processes in the design should allow for a good representation of the product's image and feel of use.

So far, no representation scheme was found to be able to fulfil all these requirements using an absolute coding mechanism.[75]

This approach does not suggest the following common requirements:

1) There is no requirement from the scheme to be useful for all audiences and all design domains simultaneously. Instead, it requires the representation scheme to allow for a seamless transition from representing one design domain to another and shifting in representing the information from one audience to another.

2) The representation scheme does not have to represent the information both completely and in absolute detail.

3) The scheme is not required to represent the information with absolute accuracy.

4) The system is not required to have a strict mapping from syntax to semantics: this suggests that the interpretation of the information can be performed by the designers using their perceptual and cognitive mechanisms. An approach to resolve this requirement is described in Stiny (1990).

6.6 Limitations and Suggestions for Further Study

This project deals with a rather large topic—sketching and design and CAID—as such, it is much more than could ever be covered in a Master's Degree Project (MDP). The exploratory nature of the work resulted in a review of large amount of theoretical material, which is usually classified outside the scope of industrial design. The intent of the work is to study and probe the problem, knowing that not all the encountered questions will be answered here. Some issues were recognised during the project and are still left unresolved; for example, the theoretical review shows that design sketching is a means of external thinking, but this study does not find how this happens or why; these questions require much more research[76] than can be accomplished in this MDP.

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[75] An absolute coding mechanism here refers to a coding mechanism, which is based on an absolute representation system like Euclidean geometry. A discussion on this topic can be found in "Sketches of Thought" (Goel, 1995).

[76] This question is the topic of ongoing study in several research institutions around the globe, involving many researchers and much effort.

The empirical observation conducted in this project is limited in scope and includes only a qualitative analysis of a small amount of data. This suggests that additional data must be analysed in order to validate the results given here.

It is recognised that this study is merely an exploration covering theories on the subject of sketching and CAID, and even if all the theoretical questions are to be resolved, much work is still needed in order to implement the results and create a workable CAID tool.

It is important to remember that CAID like any other tool is based on existing practice patterns, which are bound to change with the introduction of a new generation of CAID tools. This cycle is to be repeated until the pattern of work and the tool merge successfully.

The following questions are left unresolved at this point:

1) Sketching is a form of external thinking; how does it occur, why, and what does it require from the representation scheme used to facilitate it?

2) Extended knowledge is shown to be an important part of design representations; can it be used in computerised environments and how?

7. Appendices

Appendix A - List characterising design type processes

Appendix B - Akin's heuristic rules for design

Appendix C - The design problem selected for the observation

Appendix D - Protocol of session 3

Appendix E - Design sketches produced by Participant C in session 3

Appendix A

List characterising design type processes

Goel (1995, pp. 85–86) suggests the following twelve-point list which distinguishes between what he calls design type processes[77] and non-design-type processes:

1) Availability of information: no clear initial states, goal states, and transformation functions.

2) Nature of constraints: constraints in design are generally of two types: nomological[78] or social/political/legal/economic. The second type is regulative and negotiable.

3) Size and complexity of problems: design problems are generally large and complex.

4) Component parts: being large and complex, design problems have many parts, but the structure of the problem is not helpful in the process of decomposing them.

5) Interconnectivity of parts: the components of design problems are not logically interconnected, but have contingent interconnections.

6) Right and wrong answers: there are no right and wrong answers in design, just better and worse solutions.

7) Input/output: the input in design is information about prospective usage, and the output is information about the products. The connections between input and output are the representation schemes. Goel suggests that "the qualitative difference between the input and output information and the several distinct problem-solving phases results in orthogonal abstraction hierarchies" (p. 92).

8) Feedback loop: there is no inherent feedback while designing, which suggests that the lessons learned in the process can only be applied to the next ones.

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[77] Goel's discussion combines notes about the design process and the design problem because they are inherently replaceable.

[78] Nomological constraints are dictated by a natural law, and are therefore, non-negotiable. They are not useful for defining and constituting the design task (Goel, 1995, p. 85) because they do not direct the design process.

9) Cost of errors: every design move has associated costs and benefits.

10) Independent functioning of artefact: the designed product has functioning independent of its designer.

11) Distinction between specification and delivery: the outcome of the design process is merely a representation of the product and usually not the product itself.

12) Temporal separation between specification and delivery: there is a time separation between representing the artefact and creating it.

Appendix B

Akin's heuristic rules for design

Akin draws the following fifteen heuristic rules for design:

1) Singular solution: Design often involves multiple representations, each dedicated for representing certain aspects of the design solution.

2) Divide and conquer: Constraints in design, which usually refer to many aspects of the design problem. Akin uses constraints as related to the various components of the problem, such as, design variables, criteria and requirements.

3) Time sharing between solutions: Multiple partial solutions each responding to separate sets of constraints requires the designer to focus his/her attention on each set at a time. This way of dividing attention resources in time between different aspects and components of the design requires additional steps for integrating these separate sub-solutions into a complete one.

4) Decision hierarchy: Each design decision has its own level of importance, generally earlier decisions are more important than later ones. There is a hierarchy in design decisions based on composition and functionality.

5) Conflicting unequal constraints: When two or more partial solutions with unequal importance conflict, the conflict can be resolved in favour of the more important constraints.

6) Most constrained first: When a number of constraints are to be satisfied, a procedure for allocating attention between them must be found.

7) Representation selection: As the focus of attention is shifted between constraints, designers must shift from one representation, suitable for representing the first constraint, to another more suitable for representing the other.

8) Solution testing: Partial solutions developed for particular constraints respond differently to other constraints, this requires one to check each solutions response to a variety of constraints from time to time.

9) Search in uncertainty: Unlike cases of deterministic processes, designers often require a wide range of information which is often not available. In such cases designers need to work with assumptions.

10) Simulation of constraints: Solutions to design situations are usually based on past experiences. Some cases include solutions that are unacceptable a-priori. These solutions must be tested through whatever means are available before they are accepted.

11) Hedging the bets: If testing of a partial solution does not yield the sufficient information then redundant solutions can be used to insure success.

12) Sequential processing: When several alternatives are developed simultaneously, one must be selected for detailed handling at each point in time.

13) Constraint hierarchy: Solutions should be developed in response to previously known functional and compositional dependencies in the system.

14) Least promising first: Selection between multiple possible solutions is biased by designers' preference, often leading to the selection of the most obvious choice. In order to avoid this, designers should evaluate the least promising ideas first.

15) First idea: Designers often tend to bias in favour of their first ideas and develop these ideas before evaluating them.

Appendix C

The design problem selected for the observation

Your client:

MagnifEye is a medium-sized company, in the past five years it has established a substantial market share in the field of computerised, enhanced vision aides. MagnifEye develops and manufactures computer enhanced sight equipment for the aircraft industry and to the military. MagnifEye has recently decided to develop an application for the auto-industry in collaboration with General Motors. The new product, a wearable computer for automobile technicians, combines MagnifEye's expertise with funding and support from GM. The new product is intended to utilise knowledge based augmented vision; the product will assist technicians in diagnostic and trouble-shooting procedures in servicing GM cars.

Product background:

Knowledge based augmented reality (KBAR) is a mechanism which superimposes information, generated from available knowledge, on the existing image received from the physical environment. An example of this system is given in Figure 1 (Feiner, Macintyre, and Selligmnan, 1993; Selligmnan, 1994).

Figure 7.1: a Knowledge Based Augmented Reality system intended for assisting in maintaining a photocopier. (Selligmnan, 1994).

Your Job:

You have been asked by MagnifEye to design a system for their collaboration project with GM, which will answer the following objectives:

1) Has an aesthetic and dynamic form.
2) Is comfortable and fits the human body.
3) Easy to use.

4) Fits the environmental conditions, existing in a automobile workshop.

Required system components:

a) Visual system including goggles with computer screen

b) Audio system including an earphone, a microphone is an option

c) User controls; may include keys, buttons, levers, etc.

d) Central Processing Unit (CPU)

e) Memory connected to the CPU, most probably a hard drive

f) Power supply and battery.

Additional information:

The product is planned for initial production run of 10,000 units; if successful the run would be extended. The price tag is still unknown.

Appendix D

Protocol of session 3

1:04:00 The board, the crawl on.

1:04:20 they need to lie on a "crawler".

4:26 lap-top hard drive size, that's 3"x3"x1"

4:30 cellular phone size 2"x3"x1"

5:03 this means this thing is going to be fairly small.
This means there are two ways I can go: I can go either with a hard body shell or I can decide to, eh, encase that thing in a soft, eh, exo-skeleton, ... I guess, ...so.

1:05:23 (starts sketching)

1:05:28 kind of objects (feels his hip area)

5:33 coming through here (from hip to front of chest) (sketches pentimenti -basic forms)

5:50 (feels hip area) through here, add side panel to (relatively flat) original shape.

5:59-6:15 do you have a bigger flatter coloured pencil (looks for a "fat" pen or coloured pencil)

1:06:15 (oversketches - traces over outer lines with felt pen, defining shapes)

1:06:29 so, ...(feels hip) tuck that around, I'm trying to just imagine the torso (turn paper 30° cw)

1:06:38 I'm just trying to think about something that's gonna maybe, control... (sketches) if I can put it off to the side, ... and maybe have a (sketches) plate, a soft plate that comes around and grabs me (grabs his hip with his hand)

6:51 so that it's not flipping around, you know... something that can (sketches) can... can control that surface. (Changes pen to thin)

6:57 that's kinda one of the concerns, but then if I go and lie on my side (feels his side)

7:04 what I can do actually... if I've got sort of the hip area here (sketches the lateral section of the hip area) and then (feels his hip an shoulder)...

7:21 if I can use that space (draws a straight line connecting two points along the hip curve)... I've got that space, then I look at my spine as well (feels spine at lumbar area), ehm...

7:28 I could potentially use, use the lumbar area... right in there, to keep that nice and flat (oversketches the combination of curve and straight line - as a single entity)

1:07:37 so that kinda suggests, ... ehm, a form that comes along (sketches) through here (moves hand along a horizontal line which represents both side of the hip and back of the lumbar) (a single representation element has two different meanings)

7:37 Yeah, OK, ... so.

7:50 (starts sketching on a new page)

7:55 So, I'll tuck him in (sketches) there, come through (sketches)

1:08:02 how he probably wants to be (sketches), on the flat side, so (sketches) how, what, ... want to terminate. (feels hip) that actually want to terminate (sketches) sort of along (sketches) that line (sketches).

8:20 just sorda thinking about (sketches) clay and, if I was to have a form, ... an "hourglass" shape (feels side) how would, ... I feel with that clay, you know, what would, what would that look like.

8:40 so, in terms of sketching, "y'know I tend to sort of, when I build. ...My background is in sculpture, so in terms of drawing. I tend to work on drawing the way I work on, (sketches) work on clay, is that I start off with a block (sketches), and then I sort of imagine hacking at it and. (sketches) if I'm going to hack away that edge, I'm going to hack back at that edge (pointing at opposite edges of the 'block')

1:09:00 and very much sorda think thinking about it in terms of 'a 3 dimensional object' as if it was a piece of (sketches), as if it was a piece of clay

9:10 and then, cause then I don't worry about it and it helps me sort of define a space as well.

9:19 so, if I come through (sketches)

9:21 I want that (sketches) ...probably be fairly flat (sketches) through there...

9:30 now this guy, ehm

9:35 yeah he'll have to be fairly thin (sketches), go down through there, (sketches) and come along a little more (sketches) around here, (sketches) so what's he gonna do here (touches his waist)...

9:49 he's gonna come along there and sorda to that (sketches pentimenti)

9:56 (switches pen to thick) so then, once I sort of gotten that far ... then I sorda go over it again to try to clarify ... so I have a better understanding of what that object is and how that would fit in there

10:29 (reflects while sketching) ehm, in terms of servicing this thing...

1:10:31 ehm, how often do you need to get into this object?

10:38 Experimenter: not often, rarely.

10:39 OK, so both power to it, battery that we can charge externally?

10:45 Experimenter: ...or take it off, it's your option...

10:49 OK, ... so that guy (sketches) needs to come out some how (points out the location of the power supply subsystem for the first time)

10:54 that probably gonna do that (sketches)

10:58 (rotates sketching surface 90ccw to fit its orientation on the body) (reflects) OK, so wearing it...

1:11:04 so coming down (sketches) through here (fills his side from hip to underarm and back down) this guy wants to be as thin as possible, ... I would think...

11:13 (starts a new page, places the previous one as a template underneath it, still in vertical orientation)

11:24 OK than (switches to thin pen)

11:26 so, again its just questioning me, try'n try'n clarify this thing (oversketches the lines apparent through the page to reduce its muddiness)

11:43 and what this thing really needs to be (sketches)

11:57 OK, so anyway (moves underlay pages) so that's either there (feels wrist area) (reflects) ... what other spot, ...(Reflects) can I do

1:12:04 ehm ...(Reflects)

12:10 this has to be one item? Experimenter: no

12:11 so, I can move the hard drive from the ehm? Experimenter: yes

12:19 so, what area ...(Reflects) that is negotiable (moves his char back and looks at his own body) the arms (touches the arm between the elbow and the wrist) doesn't make sense, because I probably wonna reach through and find some stuff

12:34 ehm ...(Reflects) the legs might be a candidate (touches the femur area down to the ankle)

12:37 although, that hard drive is probably ...(Reflects) you're saying we're looking at something about this size (picks up a sketch object) Experimenter: yeah.

12:43 do you know how much this thing weighs? Experimenter: no.

12:47 is that safe to say? Experimenter: that's too heavy.

12:55 OK ...(Reflects) (tries to place the sketch object representing the hard drive component in his waist-side, above his waist, and in his lumbar area) just trying to think where I can

13:15 this is good in terms of accessibility to the object y'know I can really see (simulates 3 operating buttons on the side waist position) a 3 button pad here and doing my thing.

13:20 (plays with the simulated buttons)

13:29 OK, for this exercise that's where is going ...(Reflects) (picks it up again, plays with it, checks interference with arm and wrist)

13:35 OK, so (sketches) I have (sketches) torso and there (sketches) I will probably get away with just doing that (sketches) and then (sketches, feels the drawn area—in his side—again) ehm ...(Reflects)

14:24	I would imagine there will be strapping, this little guy on
14:30	...(Reflects) ehm ...(Reflects) wonder how long a belt you need (sketches) something in through there (sketches)
14:44	and a big cowboy buckle right there (sketches) OK, so (gesturing a rectangle in perspective view without actually drawing anything)
15:02	OK so it is (sketches) coming through (sketches)
15:23	hard drive is in...
15:32	as far as the computer... I can break it up right? Experimenter: right.
15:38	I can fit that volume into other spots, so that if I say that this hard drive is what's gonna drive... the (Reflects) the volume and that's maybe what's should be, bring that guy around (sketches)
15:55	OK, so he just drops in there (sketches) and then I'll put, ehm ...(Reflects)
16:02	OK, so I'll make him ...(Reflects while sketching) symmetrical through the centre (sketches) and I'll put my buttons (sketches) following that curve (sketches)
16:14	maybe a little bit of dish (sketches) to it
16:20	...(Reflects) that way you can wear it (feels his side again) on this side (shows left side) depending on your ...(Reflects) on your preference.
16:28	Ok, so that thing will ...(Reflects) (switches to thick pen)
16:32	OK (oversketches outline with thick pen) not very complex form
16:44	...(Reflects) ventilation? Do we want to worry about ventilation or anything like that? Experimenter: no.
16:53	it's probably the enemy isn't it? Yeah, in this environment ...(Reflects switches to thin pen)
16:59	Ok, so ...(Reflects) (rotates page 90° CW) we'll have it.
1:17:05	...(Reflects) plan, (sketches a plan view) it'll look probably like...(sketches)
17:13	Experimenter: thickness can be less than 1" more like 0.5"

17:18 OK, the hard drive? OK so I can bring it down, and then elevation (sketches to front view) (rotates page 90° CCW)

17:31 he'll be doing, ehm ...(Reflects) (feels side again) (sketches)

17:32 (whispering) what he'll be doing, coming down, yeah (sketches) be doing a bit of this (sketches)

17:50 (rotates page 90° CW to original drafting orientation) and then my buttons will (gestures a horizontal line) (rotates page 90° CCW to help draw a straight line and back to horizontal orientation)

18:03 (oversketches to refine lines defining the buttons) ...(Reflects) (rotates page back and forth between vertical and horizontal orientations)

18:11 whatever. This time I'm not gonna worry about that.

18:15 (rotates page 90° CCW to vertical orientation) ...(Reflects) Ok so that's (switches to thick pen) (traces both views ends up saturating plan view)

18:40 and then I'll have a strap going off (sketches) ...(Reflects) to the torso (gesturing) ...(Reflects) I guess what we'll see is...

18:50 (switches to thin pen) ...(Reflects while gazing at the whole page)

19:00 that object (sketches) will take off, whatever buckle type...

19:08 have to be a low profile buckle, cause we're running into some problems;(feels waist) maybe we'll tuck the buckle in (sketches) (points to the connecting line between the buckle and the belt)

19:14 I'll make that... that buckle and I'll bring him into this face (sketches) so, so the object swings over and actually grabs onto the belt (demonstrates the swinging and fastening action). So, so, that whole fastening system is part of the object.

19:28 right OK, so that'll stick underneath there (sketches)

19:32 OK, so (looks at sketches and rearranges them on the table) ...(Reflects)

19:35 now the goggles, ehm ...(Reflects)

19:41 that's an interesting issue. Did these guys need peripheral vision? Experimenter: No.

19:43 so they can look straight ahead and ... Is peripheral vision a problem? Experimenter: No.

19:53 OK, so But allowing light into these things...? Experimenter: doesn't matter.

19:57 OK (starts sketching)

1:20:01 so, assuming it's a goggle (sketches) we've got that kind of affair (sketches) and this little (sketches) comes through and we can do whatever we wonna do basically

20:17 it's a goggle! Very exciting!

20:23 so I've got that ...(Reflects) kind of an idea ...(Reflects while oversketching)

20:26 how, will these guys potentially get a hit from like in the head or that thing (gestures around the head area) Experimenter: it might be.

20:30 so, ehm ...(Reflects) the idea of ...(Reflects) like ...(Reflects) a single ...

20:36 are these in both eyes, is this stereo? Experimenter: usually not, but could be.

20:40 OK, so, ...(Reflects) but the idea of coming around with a single sort of a strap that comes out in the front

20:52 Experimenter: yes that's what you saw in the picture that I've showed you.

20:52 oh, did I? Oh OK, some that's quite fragile little object ...(Reflects) I would think, so you don't wonna bump into that.

21:02 Experimenter: you can project the image directly on the glass surface

21:07 right OK, I'm just, I'm more concerned about ... when kinda limitations on the object itself (reflecting while oversketching)

21:36 and you did talk about, potentially ...(Reflects)

21:40 some ...(Reflects) hmm microphone, kind of a device, possibly (orients paper)...(Reflects)

21:56 (switches to thick pen) (traces outline)

1:22:21 so, in terms of y'know, what I do when I'm sketching, I sorda commit at different levels, like ...(Reflects) ehm for me anyway, these sorda loose gesture kinda things sort of indicate that I'm not committed to it. (Orients page vertically)

22:39 right, (switches to thick pen) and then when I start going to sort of more solid lines, ...(Reflects) I'm starting to y'know commit to the object perhaps a little bit more (switches to thin pen) sometimes, perhaps more than I should.

1:23:00 so, anyway (reviews the different elements in the sketch by oversketching) ...(Reflects and orients page horizontally)

23:15 now, where would that guy need to go to? ...(Reflects)

23:18 probably can come down further (sketches, ads shading to the existing outline)

23:28 OK this can end in there ...(Reflects)

23:34 guess the microphone's gonna be like nothing, right? Experimenter: right.

23:45 (switches to thick pen) problem is the ...(Reflects) out there further yet (switches to thin pen) (switches to thick pen) OK ...(Reflects, while orienting page vertically)

1:24:10 so ...(Reflects, by looking at the whole page)

24:12 ehm, maybe ...(Reflects) ehm maybe it would be advisable to have sorda like ...(Reflects) ehm a little spring clip so that they can (switches to thin pen) take and y'know (switches to thick pen) swing it out of the way (sketches an arrow describing the motion)

24:34 y'know, say they don't wonna take off the whole head gear they just wonna get rid of the heads-up, I don't know ...(Reflects)

24:39 ehm if that's gonna throw them off having this thing in front of their eye, but ...(Reflects)

24:43 maybe just something they can flip out of the way ...(Reflects while over-sketching)

1:25:00 anyway, (switches to thick pen) of course there's gonna be goggles which is as exciting as ... get out! I mean...

25:09 thing ...(Reflects) what, what other place we can come off, we can come off the neck (demonstrates a path for the cable around the neck)

25:18 (starts a new page) ...(Reflects) what else can we attach to this ...(Reflects) to the head

25:22 this way we can still have a hand in

25:49 comes down through a hinge point (sketches) in there and just comes along (sketches) with one.

25:59 this is ...(Reflects, over-sketching) the item comes right trough (sketches) ...(Reflects)

1:26:04 I guess really for that matter, if I'm going to be putting in ...(Reflects) one, might as well put two, right? ...(Reflects, over-sketching)

1:26:21 what about safety? like ...(Reflects) ehm would these guys be normally be required to wear goggles on line? ...(Reflects) probably...

26:37 cause I know a lot of work places now, ehm just regardless of what you're doing... Experimenter: you're gonna wear goggles anyhow.

26:45 so, Experimenter: and since these are not going to be that much different, then...(over-sketching)
yeah, there's not a whole lot of excitement there...

26:59 I guess the other thing too is that these guys are ehm ...(Reflects) I mean they're mechanics, right? So they're gonna have their own sense of aesthetic sense, of y'know , what sort of expectations they're gonna have in equipment, like they know the kinds of headbands that they wear, so, I guess they can have a sort of that sort of an idea (sketches)

1:27:25 or ehm ...(Reflects) just the traditional ...(sketches)

27:27 although its kind of nice to have a ...

27:32 everything sort of knock down, y'know, ... and then of course there's the (sketches)

27:44 that sort of an idea (sketches)

27:46 ...(Reflects and orients paper vertically) it's very exciting

27:49	but maybe, maybe it would be for the best if you're rolling around and so forth
27:55	...(Reflects) and ... (points at the nose bridge of the goggles) I would assume that the relative location of this (sketches) guy, ... to the eyes is important, right?
1:28:01	cause if this thing is sort of moving around on your face that would be a problem of some substantial amount, so (switches to thick pen)
28:11	anyway, so we're just gonna make it a band for kicks (over-sketches to select the band option)
28:21	I gotta tell you this is seriously weird for me, I haven't got a clue what I'm doing...
28:37	some sorta nose bridge thing (sketches) in there (sketches some lines to render the glass surfaces)
28:44	ehm, OK, so (switches to thin pen, examines and revisits "old" sketches)
28:51	transmission of this guy, this guy is hard wired? Experimenter: yeah.
28:56	OK, so that means that probably somewhere here (sketches) or back in through here (sketches) I've gotta come of with a ...(Reflects)
1:29:06	I'm not gonna draw a head ... forget it! imagine there's a head there
29:06	so, we're gonna come along (sketches) and I would think down the back (sketches) of the shoulder (feels the back of his shoulder)
29:22	just seem it would be in the way if it went the front (feels front path)
29:34	...(Reflects) so if we sorda come of the back.
29:35	Experimenter: you can even put it inside the clothing
29:36	well yeah, I'm just thinking about it in terms of being able to quickly use this thing ...(Reflects) I don't like to stay inside the cloths if I can avoid it
29:48	y'know if eh, maybe these things have like flexible Velcro bit that just sticks to your cloths, sort of like idea

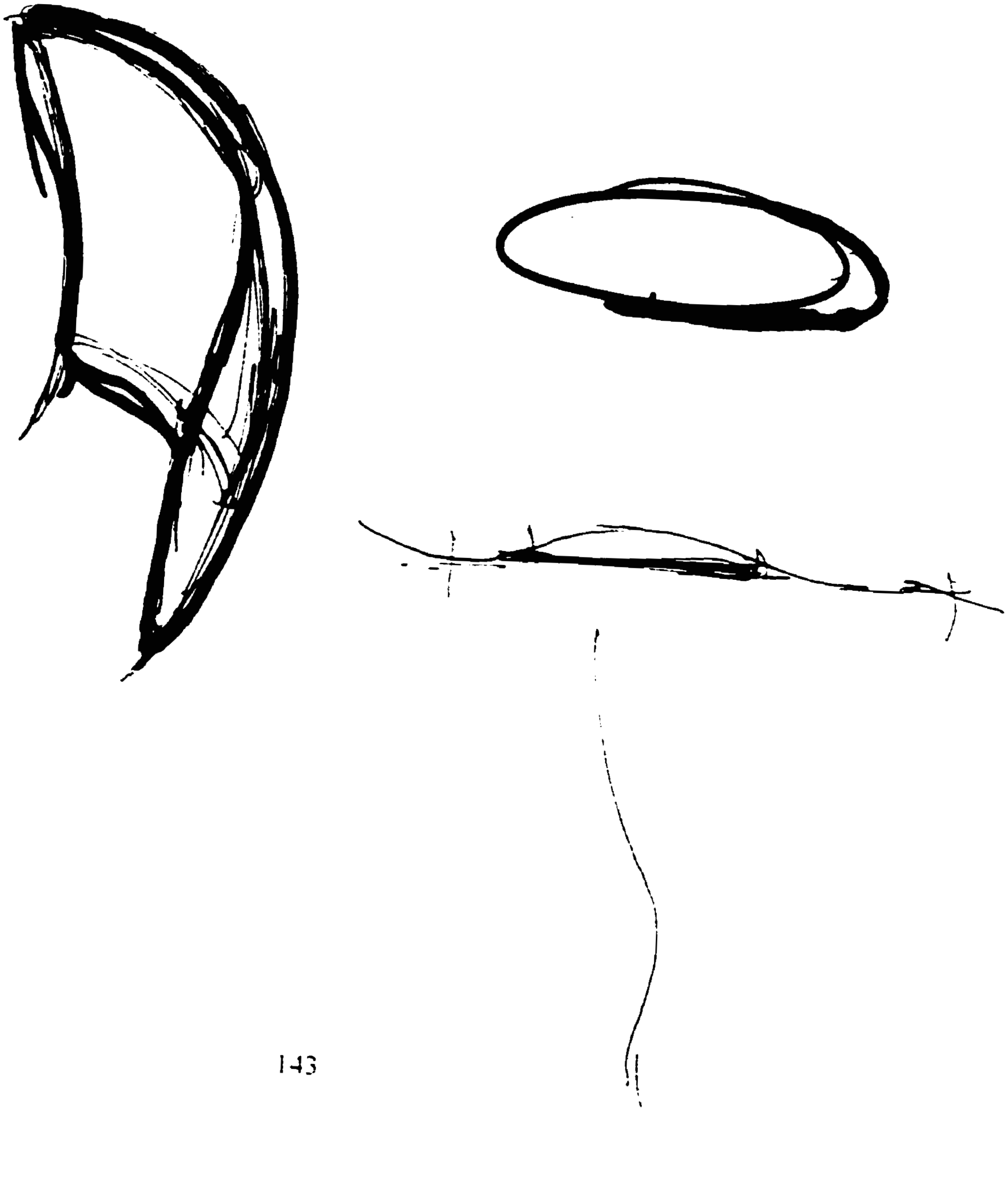
29:58	so when this thing comes down, picks up, ...(Reflects) ehm this guy here (sketches)
1:30:09	my ...(Reflects) I'm probably being (feels his waist) ...really (feels it again)
30:12	#@$, this curve needs to be more ...(Reflects)
30:17	so then it comes down and picks up this little guy (sketches) and through here (sketches button location)
30:30	so that would be sort of the wiring. (sketches) of that ...(Reflects, reviews the whole set of sketches)
30:33	now, I just wonna go back and look at this guy
30:38	(starts be positioning on the page and gesturing the orientation and the lines, without marking the page) so all I really care about this is ...(Reflects while sketching)
30:44	symmetry ...(Reflects) through that axis (marks a dashed line to represent the axis) ...(Reflects) leans back and looks at the whole sketch
30:49	and ehm ...(Reflects) (feels his left waist again) I'm coming along here ...(Reflects)
30:54	it would almost be an advantage ...(Reflects) if I can bring ...(Reflects) those buttons around a little bit more (moves his hand a little more to the front) so I'm not quite (gestures at his back)
1:31:04	so maybe that ...(Reflects) will lead the edge (sketches) a little bit more and around the back ...(Reflects and feels the spine at the lumbar area) that can be ...(Reflects, sketches)
31:20	perhaps a little less (sketches) I think that has to go (feels the location) ...(Reflects) yeah.
31:32	come through ...(Reflects, draws a curve, ...Reflects then draws the vertical guideline)
31:44	...(Reflects) OK (over-sketches) ...(Reflects and feels his side again) I guess this is not necessary, have to

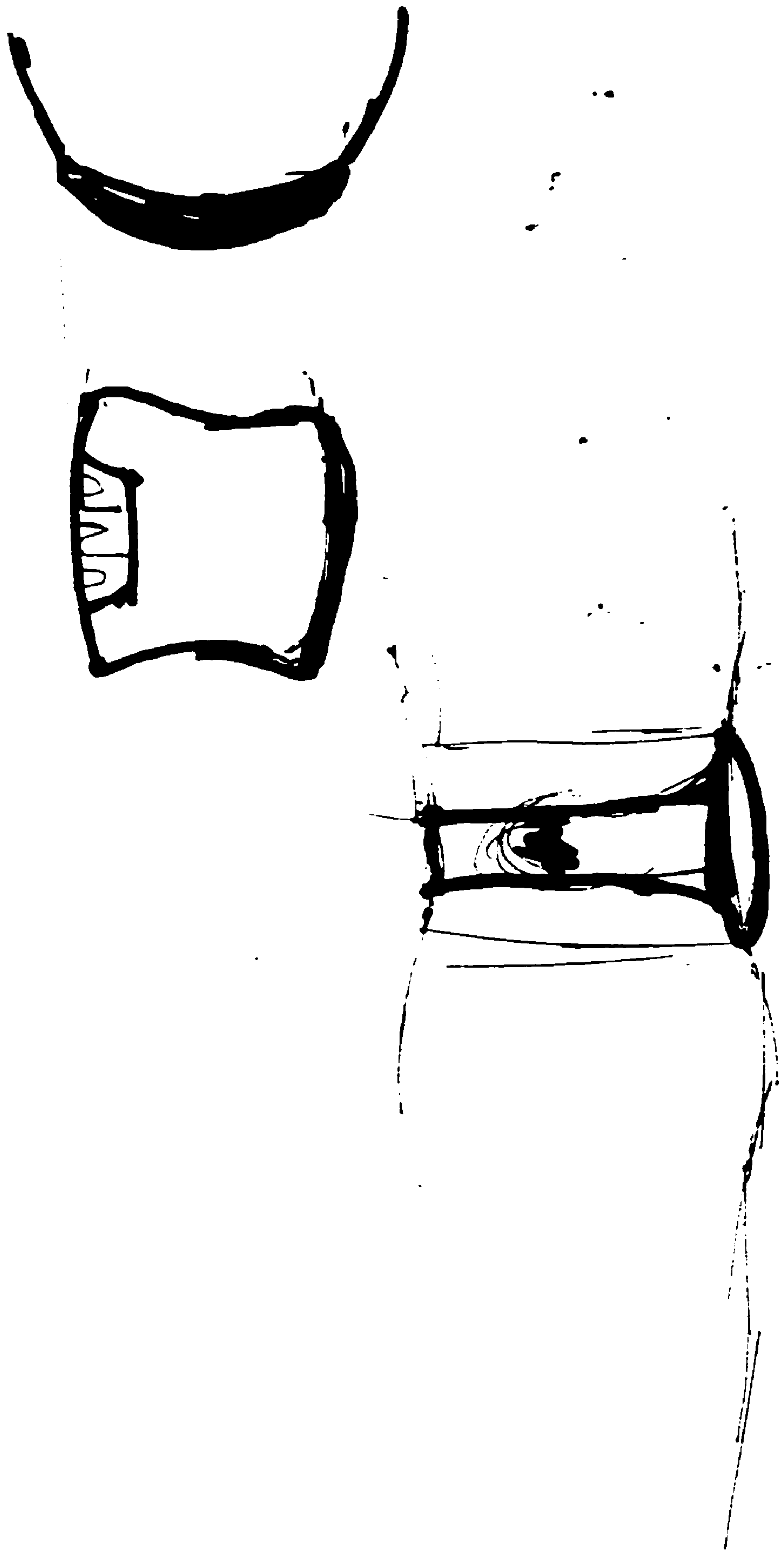
1:32:03	I'm just trying to think (feels side again) ...(Reflects) this is not quite the same ... I wonna stay away from my hip ...(Reflects, puts his hand to simulate the object placed on his side and bends sideways)
32:14	so I really got form there...(Reflects)
32:18	over (moves top oh his hand to indicate top edge of object in position)
32:20	so, how do I get the form to sort of ...(Reflects) so it's just ...(Reflects) do that
32:27	oh yeah, OK (over-sketches outline of view, Reflects and changes top curve gradually form convex to concave) let's do that about here (sketches)
1:33:19	(rotates page to vertical orientation) ...(Reflects) (switches to thick pen) I'm just thinking about just the ability to find the buttons
33:36	Experimenter: you mean tactile feeling? Well ehm just making them separate from the rest of the body, rather than, y'know, making it nice and smooth.
33:47	I think it makes some sense to try to ...(Reflects) to bring them out on there own, to their own little area here ...(Reflects looks at the whole page) so, what does that look like then ...(Reflects)
1:34:02	comes along ...(Reflects) and then this part will probably serve as this (evaluates the line by gesturing it before sketching) (oversketches the outline of the top view) yeah
34:20	(orients the page back and forth between vertical and horizontal to fit the two views) and then ...(Reflects) yeah, that still has to do that
34:32	the top is actually, the top can be flat if I want it to ...(Reflects)
34:40	yeah I can probably get away with that ...(Reflects) actually we can probably do this (sketches, extends an existing line to a whole line, redefining the outline)
34:51	take it a little smaller in the back a little more ...(Reflects) and (adds texture lines for aesthetics) I'll try to do that with it
1:35:02	I'll try to do that with it (sketches, erases lines by crossing them over)

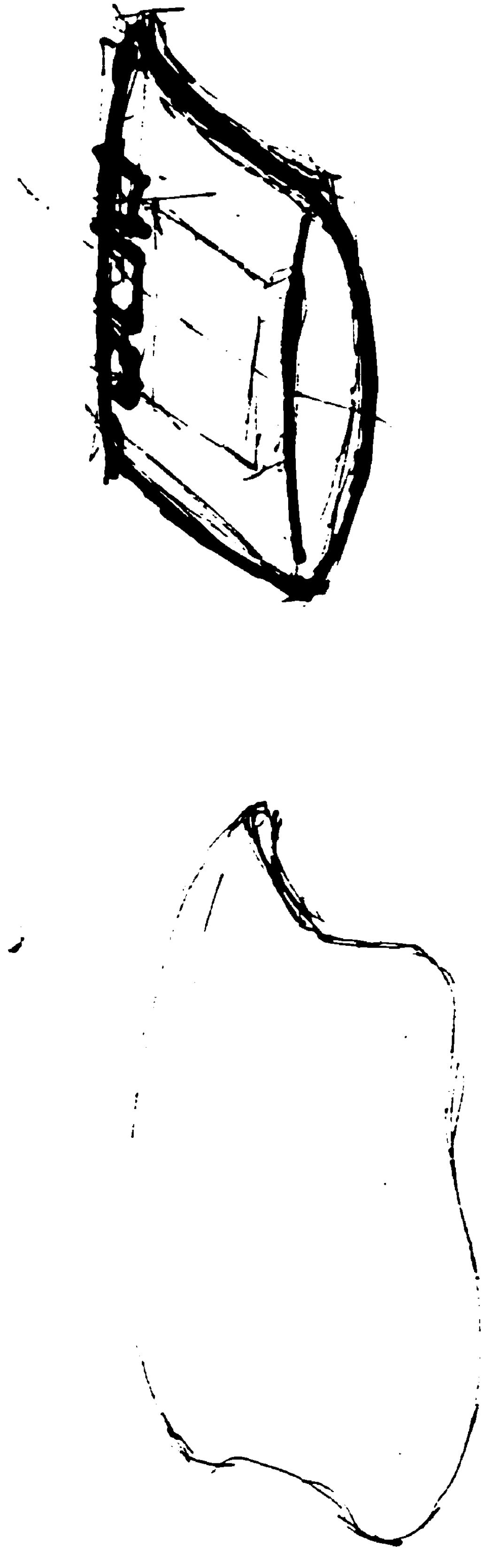
Appendix E

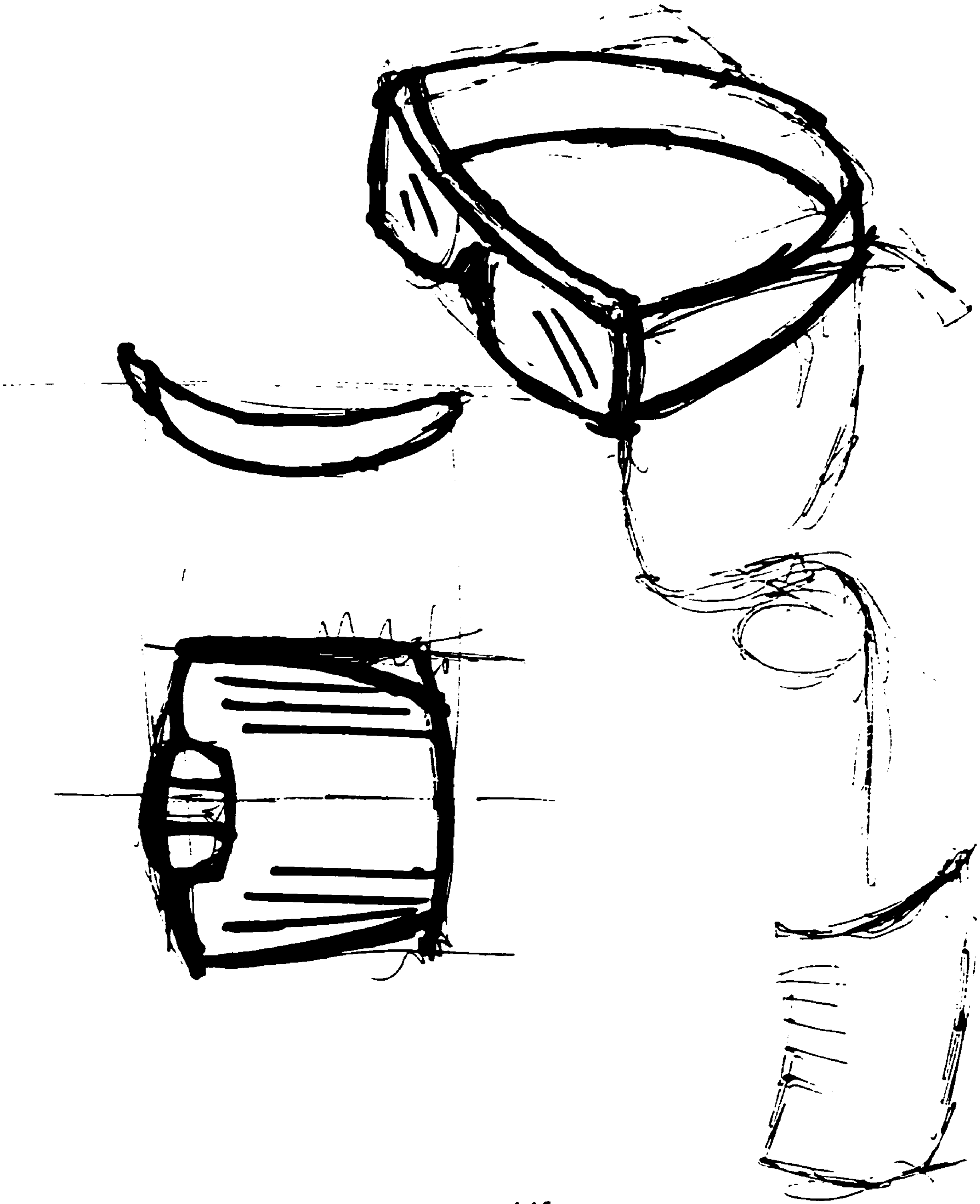
Design sketches produced by Participant C in session 3

[illegible]









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