Mental Space as a Computational Metaphor for Architectural Design

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Abstract

Hwa Ryong Lee:
Mental Space as a Computational Metaphor for Architectural Design

Despite the development of computational technology and AI over the past 40 years, it is the case that the application of computers for architectural design, especially in the early design stage, still remains in its infancy. This thesis searches for a solution, from a theoretical framework, for the computation of design, which is different from the problem-solving paradigm often adopted.

Firstly, the thesis accounts for designing as a phenomenon of design thinking-action. That is, the two activities – doing the thinking and design action – usually occur and develop simultaneously, and are characterised as a creative activity and a visual thinking process.

Secondly, in order to account for the mental mechanism occurring in design thinking-action, this thesis describes the designer's mind as with a metaphor derived from current theories in image processing research in cognitive science; the ideas of mental space. In the thesis, mental space is defined as a conscious system, which has its structure and functions that can transfer external events into inner symbolic representations (design thinking) and simultaneously visualise these internal representations during the external process (design action).

Thirdly, based on these theoretical assumptions, I propose a mental space computational model, which is a design computational environment to attempt to mimic the mental operations and processes in the architect's mental space. It focuses on design activities rather than design cognition; the usefulness of computers for design rather than the computability of design; and design tools rather than memory-based intelligent systems.

Throughout this thesis, I try to avoid the dualistic arguments which classify architectural design as either artistic or scientific, so that I can provide an inclusive theoretical foundation in explaining design phenomena for general design studies as well as for CAAD (Computer-Aided Architectural Design).

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1

Introduction

Abstract: *This chapter introduces the motivations and objectives of the thesis. It also presents the research premises, the methods and the organisation of this thesis. In addition, I account for the fields related to the research – design study, computer science, artificial intelligence, cognitive science and cognitive psychology.*

CHAPTER 1: INTRODUCTION

1.1 Motivations and Objectives

1.1.1 Motivations

Since the emergence of computer-aided design (CAD) in the 1960s, the CAD industry and research have enthusiastically tried to computerise the design processes in various ways. However, despite over thirty years of research and commercialisation, it is the case that the computer-aided design methods have achieved much less acceptance in the design domain than had been expected. Especially, in the area of architectural design, the application of computers for the practical (early)[i] design stage remains in its infancy. That is, even though some programs perform successfully a design task, being equipped with technologies that facilitate powerful graphics and sophisticated data representations, most of them contribute to only a limited extent in the design process; mainly to the later design stages.

Some design researchers have tried to develop theoretical formal models for computation of design that are intended to simulate design activities and processes. However, these models usually consider designing form the viewpoint of the problem-solving paradigm introduced by Simon[1]; accordingly, most of them are based on a computer analogy of how the designer processes information or to how they solve design problems. Even though this paradigm has provided valuable insights into scientific design studies and for the computation of design, it seems inadequate to explain design as a systematic process or a searching activity in problem space, linked to a knowledge-based activity and associated information-processing mechanism. Moreover, no consensus is agreed in the design domain about which system or theory is the superior approach.

[i] The terms of 'early design' means all design activities before the measured, detail design stage. In this stage, most designs are established and it will dominate the entire design process. Thus, it is just designing itself, in which design thinking/cation occurs so that 'designing' is used in this thesis to infer a connection with 'the early design stage'.

Thus, there are some suspicions about whether design activity falls into the paradigm of problem-solving, or at least, it is obvious that there exist some flaws in this proposition. If this paradigm has misled the directions to developing design systems, then design research should establish a new, domain-specific theoretical background for computer-aided architectural design (CAAD). Design systems also should be concocted on these theoretical bases, because this different design model posits different structures and functions of a design system mechanism.

Nevertheless, surprisingly, little work in CAAD research has been done on searching for a new theoretical framework for the computation of design; only some attempts have undertaken to make up the deficiencies in problem-solving theories. This is the main thrust of this thesis. To do so, this thesis starts with an inquiry into what the designer's actual activity and thinking entails; and what computer can do for the designer, before presenting a design model and a computational paradigm for architectural design.

1.1.2 Objectives

A New Approach to the Computation of Design

The ultimate aim of this thesis is *to propose a new computational paradigm for architectural design*. Computerising design seems to have focussed much CAAD research activity into a framework of scientific and rationalistic theories, technologies or language that is amenable to computation.

This thesis posits that the failure of design computation results not only from the lack of technologies for representing design activities in the computer, but also from the lack of understanding of the mental processes associated with architectural design. Within a problem-solving framework, design is forced into being explained with unfamiliar terminology and strategies that share a theoretical patrimony with the neighbour fields.

However, designing is involved in quite different thinking and actions from any other problem-solving activities and hence cannot be tackled by a special subset of general problem-solving strategies derived from computer science or artificial intelligence (AI). The difference should be accounted for in terms of the nature of the problems with which each domain activity is involved. That is, for a design system to be congenial to the designer, it must be founded upon the study of how the designer actually does and thinks during design processes.

Here is the significant necessity to establish a 'designerly approach[2]' that could study and model design phenomena with its own languages and its own knowledge. This is a *sine qua non* for the development of computable design systems. This observation leads the research to examine the question what are missing in the existing theoretical framework and what is needed for a new theory for computerising design. The potential answers in this thesis will be presented and suggested as a design model and as a computer model.

Beyond the Dual Structure in Design Studies

In this thesis, I intend to *avoid the art-science dualism* in design studies. A one-sided view of either art or science in design theory cannot explain design as a whole and cannot be accepted by practising designers. The dual structure must be employed only as a means of explaining constituent parts of design, not as an exclusive categorisation. Accordingly, design methods and computer systems should take account of both characteristics of art and science in designing, and then they should contribute to enhancing the designer's creativity as well as to working efficiently and effectively.

To do so, this thesis will pay particular attention to one axis of design – the artistic approach, which has been commonly ignored or regarded as a mysterious aspect in design by CAAD. This is because it cannot be modelled as a cognitive process and cannot be computerised within the problem-solving paradigm. Naturally, the design systems have overlooked the artistic aspects that play crucial roles in designing, such as creativity, intuition, imagery, or imagination. This thesis attempts to account for their functions in the design process and in designing computer systems.

In this theory, however, I intend not to defend irrationality in the design process or propose a mystic appeal to non-rational intuition. Rather, I try to suggest a new paradigm by complementing the other axis in design, which has been underestimated by CAAD research. That is, this thesis will examine, with scientific attitudes, how artistic aspects influence design phenomena and how they can be implemented in computer systems. Thereafter, I will propose a design model and a computer model that can accommodate both the artistic and the scientific stands in design.

1.2 Research Methods and Thesis Organisation

1.2.1 Research Premises

This research is pursued under two fundamental premises: (1) designing is involved in self-conscious activities; and (2) computer-aided design is a potential design environment.

Designing is involved in Self-Conscious Activities

Design studies usually begin with the rejection to the viewpoint of design-as-mysterious process; that is, they regard design as a 'self-conscious process[3]'. The designer prepares a plan, anticipating, imagining and guessing the consequences of his/her activities. In addition, their activities are performed with certain objectives and constraints; are evaluated by some criteria; and hence are self-conscious.

Of course, some of design activities may appear in a subconscious way, and the conscious representations may be invoked only when processing does not run automatically. However, the product of design results from effort and conscious mental processes, involved in design thinking, understanding, reasoning, imaging, and design actions. That is, architects intentionally derive and develop design ideas or inspiration from their own accumulated knowledge and experience rather than from an unconscious dream state. Rittel's (1995) notion vindicates this research assumption: "design is not spontaneous; it is a deliberating and anticipating activity"[4]. Accordingly, this thesis considers designing as a conscious activity and as a phenomenon that can be observed and explained.

Computer-Aideded Design Is a Design Environment.

Another premise of the research is that computer is one of the several design environments used in performing design activities. Design environments represent tools, techniques and support systems employed by the designer and design teams during the product development process[5]. Thus, CAAD can be seen as one of these design methods that aim at an efficient, fast design process and a better product.

This thesis questions the proposition that computers can be a thinking machine that can replace human designers. Rather, it posits computers as equipment for supporting the designer and hence its role is evaluated in terms of the usefulness for designing. Thus, this research focuses on the designer's thinking and activity and on the priority of the designer rather than that of computer.

1.2.2 Research Methods

This research is necessarily involved in reviewing literature from various fields, such as computer science, cognitive science, cognitive psychology, as well as architectural design. Parallelled with the literature study, what is needed is some evidence about the arguments for establishing a design model and a computational theory for architectural design. To do so, I take up a particular psychological research approach related to observing design phenomena, which is different from the traditional research strategies such as a systematic analysis or a protocol analysis.

Generally speaking, design research has focused on trying to make explicit the general principles of design or design process, and on formulating a design model, by characterising design in terms of the scientific properties of systematic mechanisms and information processing. In contrast to the scientific approaches, Eastman (1968) attempted to remove some of mystery about the architect's mind[6]; that is, the protocol analysis. This initial psychological work was followed by many design researchers. However, this research method has some limitations in capturing the non-verbal thought process going on in design work. Lawson and Scott (1995) argue, in a paper on protocols, that although concurrent verbal reports can reveal some aspects of design thinking, there are many types of design thinking that remain impervious to verbalisation, requiring different methodologies for analysis[7].

Thus, instead of such an information-processing based approach, this thesis will employ the approach of 'introspective observation from drawings[ii]' as the way to investigate design phenomena. The introspection approach is one of the

[ii] As an alternative to protocol analysis, Galle examined the designer's thought process in the early creative phase of sketch design by the method of introspective observation. *See*, Galle, P, 'Introspective observations of sketch design', *Design Studies*, Vol.13, No.3, pp.229-272, 1992.

experimental psychological methods and it assumes that people are apparently able to report on the content of, and certain operations associated with their mental existence.

In this thesis, drawing is considered as motor processes involved in the performance of design actions. Thus, the designer's drawing is regarded as an extension of the internal mental feature, and this internal representation could be inferred from the analysis of external representation – the drawing or sketch. That is, the protocol analysis uses the method of 'thinking aloud' that is interpreted into the words, meanwhile this approach analyses the designer's mental operations by observing *drawing*.

Of course, this approach also is not an ideal or perfect approach to examine design thought and activities; it may fail to elicit important information and can be confused by the observer's subjectivity. Despite these caveats, I use it as a method of psychological enquiry on the designer's mental process. Because, this introspective approach may be a better method in studying the designer's mind than other methods, in that it focuses on the visual-graphic mode of design thinking, opposed to protocol analysis and interview[iii] method in which design must be verbalised before study. In this sense, Groák (1992) predicts that we shall increasingly use graphic methods as a formal research tool in studying the design thought:

> "Drawing is a form of thinking, not merely a record and presentation of a thought already completed.[8]"

Based on this idea, I note below particular references for the introspective observation of drawings, which help to draw some observations about the designer's activities in the early design stage.

- *Drawings from the Le Corbusier Archive*, A.Tzonis (ed.), AD Editions Ltd, London, 1986.
- *Le Corbusier Ideas and Forms*, W.JR Curtis, Phaidon Press Ltd., London, 1992 (2nd ed.).

[iii] For example, the interviews with architects conducted by Lawson, *see*, *Design in Mind*, Butterworth-Heineman Ltd., Oxford, 1994.

- *Design in Mind*, B.Lawson, Butterworth-Heineman Ltd., Oxford, 1994.
- *F.L. Wright and Johnson Wax Building*, J.Lipman, Rizzoli, 1986.
- *The Art of the Process: Architectural Design in Practice*, The RIBA, London, 1993.

However, most of drawings in design process are so personal that other viewers can easily misunderstand them. Each designer employs his/her own convenient short-hands, and most symbols used in design are for self-conversation. There are fewer conventions relating to sketches in the early design stage than there are in the drafting stage. Moreover, each designer has his/her own design habit and attitude in designing. It is therefore not easy to interpret design activities through the observation of design drawing and to develop into a design model.

Within such limitations, this research does not attempt to articulate the designer's particular personal mental operations, but instead aims to examine, in the broad sense, how the designer represents design thoughts and visualises them; what constitutes the mental visual images; and how they operate in the design process.

1.2.3 Thesis Organisation

This thesis is in three main parts: an investigation on the nature of design and the uses of computers (chapter 2 and 3), a theoretical establishment of a mental space approach (chapter 4 and 5), and the proposal of a computational model for architectural design (chapter 6 and 7) as follows:

Chapter 2: Design as a problem-solving process

Firstly, I examine the nature of design, which is usually explained by two extremes – art and science. I review the two viewpoints and discuss the need to avoid this dual structure in design theories. Then, I inspect a theoretical framework for CAAD that regards designing as problem-solving or information-processing. Through this review, I account for the reasons why the problem-solving paradigm dominates CAAD studies. Then I describe three influential streams in modelling design activities.

Chapter 3: Computers for architectural design

In chapter 3, I investigate the application of computer for architectural design, ranging from the commercial applications to AI in design. Based on this study, I present two trends in CAAD research and new directions for CAAD. However, it is identified that, despite the development of technologies in computing and AI, the computer in the design domain has a restricted use.

Chapter 4: An architectural design model: design thinking-action

Understanding the designer's activity and design process are prerequisites for the computation of design. Thus, I point out, in chapter 4, some misleading, exclusive assumptions for computerising design made by the problem-solving paradigm, and then I propose a new design *thinking/action* model as design phenomenon, following the introspective observation from existing design drawings. I suggest two salient features occurring in design thinking/action – creative activity and visual thinking.

Chapter 5: A theory of mental space

This is one of the most important chapters in the thesis – a theory of mental space. Throughout the previous chapters, I identify the limitations of the problem-solving paradigm and the distinctive characteristics of design activities. These properties cannot be explained by prevailing cognitive theories or problem-solving theories. From this observation, this chapter presents a new theory that can help to explain the design *thinking-action* phenomenon and can give insights into a potential computer model for architectural design.

Chapter 6: Mental space as design medium

This chapter discusses the mental space functions in the design process. I propose the components that are represented in mental space: objects, relationships, and events. They will be fundamental elements in mental space systems as well as in mental operation. In addition, I examine the roles of knowledge and imagery in mental space, where both interact and help each other; yet serve their discrete functions in developing designing.

Chapter 7: Mental space as design computational metaphor

From previous theoretical assumptions, in the last chapter, I focus on implementing mental space as design computational metaphor. Most cognitive systems have been interested in memory system imitated as a database, knowledge-base, or case- base. However, I identify that the mental operations during designing mainly occur in mental space, independently of a memory system. From this, I demonstrate the functions of mental space and suggest some implications for future CAAD systems.

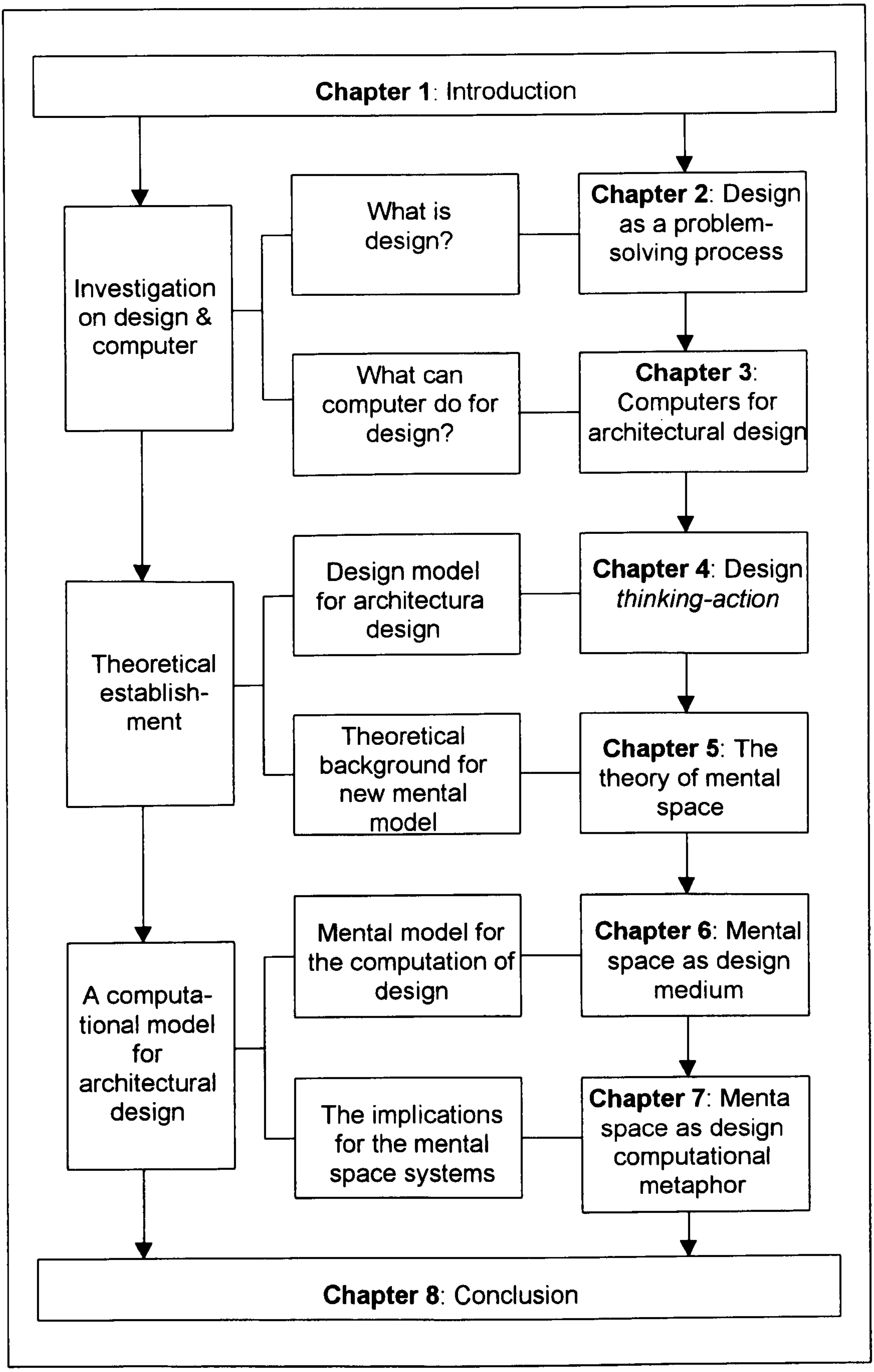

Figure 1-1: The flow chart of thesis process

1.3 The Related Fields to the Research

CAAD researchers do not invent their theories in a vacuum. Rather they may apply or adapt the theories of other sciences to architectural design. Thus, CAAD is a multi-disciplinary research field[9], interconnecting many disciplines such as design theory, architectural theory, computer science, cognitive science, psychology (especially, cognitive psychology) and philosophy.

1.3.1 Design Studies and CAAD Research

Alberto (1984) argues that:

> Theory in any discipline, especially today, is generally identified with methodology; it has become a specialised set of prescriptive rules concerned with technological values, that is, with process rather than ultimate objectives, a process that seeks *maximun efficiency* with *minimun effort*[10].

Within this philosophy, design study also has been seeking the principles, practices and procedures of design in a broad and general sense.[11] Thus, its central focuses are on how designing is, and might be conducted; that is, standardising design processes and formulating design methods.

In this regard, this research premises that computer-aided architectural design (CAAD) lies in an extended line from design methodology. That is, CAAD research is regarded as one area in design method studies that focuses on methods that reduce the architects' repetitive activities. Both design methodology and CAAD share the same premise of design as a self-consious activity, in which design can be enhanced by designerly efforts; they share the same goals to help rapid designing and to help make right design decisions. Naturally, both develop the their theories by means of the scientific reflections on design activity and process and hence both lines of research belong to a scientific discipline.

In sum, while design studies involves a scientific inquiry on design process, methods, techniques, design knowledge and its application; CAAD research is one field in design studies, stressing the computer's roles in the design process. Both share the same objectives, values, and research methods. Accordingly, the theoretical background for CAAD should be founded on design studies and its theories. This research, especially in chapter 2 and chapter 4, derives the theoretical bases for my argument from the existing architectural design theories.

1.3.2 Other Sciences Related to the Research

Computer Science and Artificial Intelligence (AI)

Since the application in computer systems can occur only through use of the expertise of computer science, the developments of CAAD are inevitably affected by the advanced computational techniques of **computer science**, such as programming, data representation, graphic technique, computer architecture and so on.

Among the branches of computer science, **artificial intelligence** (AI) has influenced CAAD research significantly. AI has tried not only to create the systems able to perform intelligent tasks effectively but also to discover the human cognitive process. Thus, AI research has provided the design field with some insights in understanding how the human designer operates and how computers can be used for design, as well as devising effective design problem-solving systems. Chapter 2 will review the applications in design domain and the contemporary technologies of computer science and AI. In addition, I will apply this knowledge to develop the notion of mental space systems in chapter 7.

Cognitive Science and Cognitive Psychology

Understanding the cognitive activities of designers is widely considered as a prerequisite for developing effective and efficient design systems. Naturally, CAAD research has, in recent years, been concerned with cognitive science and cognitive psychology.

Cognitive science can be considered as a sub-field of artificial intelligence[12]. It is relatively a new discipline that unifies theories of human thought and language within the rational tradition, such as problem-solving, artificial intelligence, or computer science[13]. Thus, it would be better to view cognitive science as a multi-discipliary approach to the study of cognition. In contrast to cognitive psychology, cognitive science has generally focused on how intelligence works and on how one would go about constructing a machine that would deal with a wide variety of tasks as intelligently as humans do.

On the other hand, **cognitive psychology** is the branch of traditional (experimental) psychology dealing with cognition. Both lines of research focus on the components and mechanisms of any intelligent system, whatever human or computer, and the interaction of these components[14]. Thus, when we present or simulate the designer's cognition in a computer program, both disciplines' technology and theory are required.

This thesis also takes advantage of the well-established theories in both fields to understand the designer' cognition and the information-proccessing mechanism in chapter 2 and 4. Most significantly, the **imagery theories** in cognitive psychology have given this thesis a significant push to flesh out *a theory of mental space* in chapter 5 and 6.

Reference

[1] Simon, H.A., *Science of the Artificial* (2nd ed.), MIT press, Cambridge, MA, 1981, stated by K. Dorst and J. Dijkhuis, 'Comparing paradigms for describing design activity', *Design Studies*, Vol.16, No.2, pp. 261-273, 1995.

[2] John, J.C., 'Designing Designing', *Design Studies*, Vol. 1, No.1, pp. 31-35, 1979.

[3] Alexander, C., *Notes on the Synthesis of Form*, Harvard University Press, Cambridge, 1964.

[4] Rittel, H.W.J., 'Impressions of architecture 130', *Design Methods: Theories, Research, Education and Practice*, Vol.29, No.1, pp. 2128-2136, 1995.

[5] Sivaloganathan, S., N.F.O. Evbuomwan, A. Jebb and H.P. Wynn, 'Design function development – a design system for the future', *Design Studies*, Vol.16, No.4, pp. 447-470, 1995.

[6] Eastman, C, 'Explorations of the cognitive processes in design', in *Department of Computer Science Report*, Carnegie Mellon University, Pittsburgh, 1968.

[7] Lawson, B. and P. Scott, 'Can concurrent verbalisation reveal design cognition?', *Design Studies*, Vol.16, No.2, pp. 237- 259, 1995.

[8] Groák, S., *The Idea of Building: Thought and Action in the Design and Production of Buildings*, E & FN Spon, London, pp.149-161, 1992.

[9] Oxman, R., 'Observing the observes: research issues in analysing design activity, *Design Studies*, Vol.16, No.2, pp. 275-283, 1995.

[10] Alberto Pérez-Gómez, *Architecture and the Crisis of Modern Science*, The MIT Press, Cambridge, p. 5, 1984.

[11] Ullman, D.G., 'The status of design theory research in the Unite States', *Design Studies*, Vol. 12 No. 4, pp. 204-207, 1991.

[12] Shank, R.C., 'How much intelligence is there in artificial intelligence?, *Intelligence*, 4, pp.1-14, 1980., quoted by R. Sternberg and P. Frensch, 'Intelligence and cognition, in *Cognitive Psychology*, John Wiley & Son, Chichester, pp.57- 96, 1990.

[13] Winograd, T. and F. Flores, *Understanding Computers and Cognition*, Addison-Wesley Publishing Company, Inc., Reading, p. 23, 1987.

[14] Sternberg, R. and P. Frensch, 'Intelligence and cognition, in *Cognitive Psychology*, M.W.Eysenck(ed.), John Wiley & Son, Chichester, pp.57- 96, 1990.

Chapter
2

Design as a Problem -Solving Process

Abstract: *This chapter starts with an inquiry about the nature of design. Its definition varies depends on where the focus in the spectrum, which is divided by two extremes –art and science, is placed. I will review two views of designing and discuss the need to overcome this dual structure in design studies. This chapter also reviews the problem-solving paradigm that has been prevailing in CAAD research. At the end of this chapter, I will demonstrate three design models that address this paradigm: systematic three-step design models; knowledge models; and cognitive models.*

CHAPTER 2: DESIGN AS A PROBLEM-SOLVING PROCESS

2.1. Introduction: What Is Design?

Simon (1981), in '*The Science of the Artificial* (2^{nd})', defined design as an intellectual activity with the objective of changing an existing situation into a preferred one[1]. Actually, human being continuously revises and adds to their world creating new art, new organisation, and new artefacts. It is a unique quality of human beings that has intelligence to want to change an existing state into a new one. The desire to change something leads them to design something. To produce a change in environment can be called 'designing' and the desire to generate a new environment is a creative motivation. In this context, "every human being is a designer[2]".

However, this statement seems to take an excessively broad viewpoint. We do not generally call the social and economic planner, the computer programmer or the civil engineer a designer, even though their conscious activities are recognised partly *qua* design. Thus, the meaning of the term 'designer' in this thesis will be confined to describing the professional designer such as an architect.

What, then, is the distinctive thread that picks out a professional designer? One factor that differentiates designers from others lies in their aims to try to produce something different, even though only slightly in some cases, from existing artefacts. Willem (1990) identifies design as a creative response to external events; and creative activity as *central* to design[3]. This does not mean that only the designer is involved a creative activity and that the product is an invented one, but it emphasises on the creative steps in the process. That is, the designer tries to be creative across the whole design process; the activity has a strong links to that of the artist.

However, the results of designing must satisfy a set of predefined function. Satisfactory solutions cannot be achieved only by confining attention to aesthetic appreciation, must include additional tasks, such as problem-analysis, decision-making and judgements, applying user's goals and constraints in a specific situation.

In this way, designing depends also on the accumulated knowledge and experience stemming from personal practice or research. The intellectual effort to arrive at a perfect or reasonable solution is similar to that of the scientist.

There exist two apparently contradictory viewpoints of designing – the art-like and the science-like view, and hence the definition of design varies depending on where the focus in the spectrum lies. This dualism of the present theoretical situation in architecture makes it difficult to offer a simple definition a design[4].

Accordingly, instead of aiming to produce a (computable) definition of design, I review the dualistic conceptions existing in design theories. Based on this, I discuss the needs to overcome the dualistic viewpoint of designing in order to understand the nature of designing. Then, I introduce a paradigm of *design as problem-solving*, which is the predominant theoretical framework in the design studies and CAAD community, and demonstrate three design models aimed at satisfying this paradigm – systematic design models, knowledge design models and cognitive design models.

2.2 Two Viewpoints of Designing – Art and Science

Dilnot (1981) discussed the two views of architectural design - art and science: One end of the spectrum regards design as a historic, non-systematic, art-like activity; the other is the idea of design-as-rationalism, design-as-methodology and science-like activity[5]. Such a dualistic concept has deeply pervaded the interpretation of design, in design theory and, as a consequence, CAAD research.

2.2.1 Romantic Viewpoints in Architectural Design

According to Larson (1995)[6], since the Italian Renaissance, architects have moved away from being mere craftsman and traditional builders. The skills of design increasingly became the hallmark of the architects for the elite and, later on, the central element of its professionalisation. Eventually, it entailed the exclusive syllogism of architecture: "Only architects produce architecture. Architecture is an art. Architects are necessary to produce art."[7] This is an underlying ideology in the paradigm of '*design-as-art-like activity*'.

The art here is, roughly, to represent the artist's belief, feeling, emotion, mode or both, into an object, event or environment with an expressive medium. With this view, design can be seen as representing the designer as a form-giver, and so aesthetic and private dimensions are much more emphasised than technical and social ones. These elements cannot be explained precisely because of their subjective, idiosyncratic nature. Accordingly, the ideology of artistic design makes the design process more mysterious and distances the designer from intellectual and discursive discourses of the more overtly knowledge-based professions.

Intuitive Designing

Art-like activity in design depends mainly on the designer's intuition or professional experience and defies the preconceived ideas, rules or knowledge that could guide their activities, because of the concern that the preconception may discourage the designer's intuitive creativity. This view therefore shares a common thread with the Romantic tradition in architectural history[8]. It has led the distinctive master/apprenticeship education system evident in cases, such as the Ecole des Beaux-Arts, the early of the Bauhaus and design studio[9]. Here the primary aim of design education was to enhance the openness of creative response and artistic talents rather than academic knowledge.

The earlier design methodologists tried to demystify this approach to design with sophisticated design methods. However, they fell short of accounting for certain design activities, and they later recognised that some of design activities (e.g. intuitive creativity) were not so amenable to an objective design discourse, as had been hoped[i]. That is, most practising architects feel uneasy with a set of normative principles and defy the application of systematic professional knowledge. The designer's intuitive design methods seems to be a strong fortification that differentiates them from mere craftsman, that endows them authority or validity for a privileged position, and that could never be conquered by design systems or scientific

[i] Jones, later, rejected his early systematic design methods suggested in his book *Design methods: Seeds of Human Futures* (1970). See 'How my thoughts about design methods have changed during the years', *Design Method and Theories,* Vol. 11, No.1, pp. 50-62, 1977. Archer also acknowledged that his systematic models were never accepted by practice designers. See, 'The three Rs', *Design studies,* 1/1, pp. 18-20, 1979.

methods. This is an obvious reason why this intuitive design approach has still prevailed with today's design practitioners, as the conventional method in architectural design.

The Criticisms of Art-Like View of Design

In contrast to the pure artistic activity that is defined as self-expression, designing is directed towards solving a real world problem. A new idea the designer perceived at first will be constantly developed, enriched, or diverted by the actual making-process. The changes will not always be of the designer's own choosing, and it may be objectively determined by factors quite outside the designer's control. Such factors might be something to do with costs, the availability of materials or techniques, and a change of client's requirements. Likewise, design problems usually exist not in the designer's mind but outside, with the specific requirements of the user and the culture, or certain prevailing contemporary principles. This reflects a social dimension of design rather than a designer's personal one.

The criticisms of intuitive design are more realistic in the case of the recent complex and large design projects. That is, the design system that can test a design judgement is required in order to prevent the high cost of design errors. Accordingly, Lawson (1994) warns the artistic viewers:

> "Design is undoubtedly an artistic business, but it is dangerous to confuse it with art.... We expect design to have artistic values, and yet design is also more than art, for designs must not only express appropriate ideas and values but must also be usable and work.[10]"

In the context that the designer must work for other's purpose; as a design proceeds, the designer becomes highly problem conscious. Even though design ideas are sometimes brought about from unconsciousness, the designer must make a decision among amounts of information and alternatives; that is, the designer becomes involved in intelligent problem-solving process. At every stage of design, there exists a tentative proposal, discussion, question, argument, and finally judgements in parallel with sorting, ordering, and relating information[11]. To enable good decision-making, the designer requires satisfactory methods that can support professional judgement qualities and legitimacy. These methods include systematic procedures and known techniques in terms scientific and verifiable. In this context, another property of design – rationality - is issued, which depends on reason and knowledge rather than on emotions, feelings, intuitions and the like.

2.2.2 Rationalistic Viewpoints in Architectural Design

> "Everyday life presents us with certain simple vertices. But, it seems, through science and only through science can we build upon these verities, and with astonishing results.[12]"

As reflected in Amstrong's (1990) statement above, particularly in our 'uncertainty age', we cannot help relying on science to obtain an objective veracity in our activities. Reference to a dictionary shows that 'science' is defined as a systematic and formulated knowledge (political science); a branch of knowledge conducted on objective principles involving the systematised observation of and experiment with phenomena (natural science)[13]. Thus, the rationalistic viewpoint implies that designers carry out a scientific process in designing, that is, they predict and discover a solution (fact) which already exists in the same way that a scientist acquires and manipulates knowledge in order to establish the veracity of a theory.

The view of science-like design has a cognate relationship with Rationalism (or Positivism[ii] in architectural history). Architectural history generally has it that the rational tradition in architectural design rose to prominence in the Baroque with Galileo Galilei and Descartes: its common theme is that certain knowledge must exist in an objective world external to the individual mind. In this view, designing is regarded as finding a reasonable solution in pre-existing facts, and nothing more than satisfying functional requirements. [14]

For More Efficient Designing

The proponents to this rationalistic view claim that recent building projects have become too big and complicated to depend solely on personal artistry. That is, today we live in a world in which technological development, together with social and

[ii] In the Positivist's view, the designer simply discovers a form already prefigured out in the world, thus, they have took the Christopher Alexander's early line that design is a scientific process of discovery.

economic change are so rapid, and buildings have become so complex that the traditional architect-centred design process is no longer feasible. This standpoint has led architectural work to be seen primarily as a business involving project management[15] that focuses on efficient, profit-motivated goals.

In this regard, the designer is required to bear higher professional competence: knowledge for solving a problem; skill for increasing efficiency; and responsibility for the quality both of the building and the social and cultural environment. This competence is employed as instrument in improving the efficiency and reliability of production, and in adapting and developing production procedures to suit particular products[16]. Thus, as proficiency and knowledge in designing become emphasised, it is apparently unavoidable to involve a scientific design process to gain the reliability in decision-making.

The major belief of this viewer is that the systematised design process and methods help designer to produce a better design in more objective ways. The process of designing is usually seen as a series of systematic procedures that can be explained with a flow chart and can be controlled by a set of design rules and principles. In this process, design can be done through the synthesis of a series of sub-problems that are solved by well-known design methods. Thus, it is prescribed as searching for a solution that is already predicted in design knowledge or potentially contained in the information from the client's needs, like any scientist who searches a rule of nature. From this observation, many design studies have tried to discover more general design methods and acceptable systematic processes or design knowledge for effective, efficient or better design.

Rationalistic Viewpoints in CAAD

Design methodologists and CAAD researchers could not avoid the rationalistic viewpoint of design, because their methods or systems have relied on scientific concepts such as systematic design process, design methodology, and scientific design methods. Such scientific attitudes involve predicting the consequences of an action, and then evaluating or testing the action itself and future outcomes through examining the cause-effect relations in design problems. These relationships are represented in the form of mathematics, certain laws, rules, algorithms or design principles. They can be interpreted by a symbol and provide a valuable medium with which design processes can be modelled in computers. It is for this reason why CAAD researchers have clung to such rationalistic attitudes to design.

But, even though this rational attitude may contribute to the analysis of the massive and complex design information available or to devising some logical design models and systems, there are no existing design models and systems successful enough for the designer to exploit in practical design. This is because design is not an activity of simple reasoning from fixed objects or parameters. Thus, along with the art-like view, this rationalistic one also is deficient in explaining the activities involved in design. In the next sections, I articulate some dichotomies in design discourses, and argue the need to avoid the dual structure in design studies.

2.2.3 The Dual Structure in Design Studies

In a philosophical respect, the split standpoints in design studies originated from mind-body dualism and the subject-object distinction in a philosophical system about the individual and his relationship to the world[iii]. That is, on the one hand, the individual can be thought of as a physical object in nature whose actions and behaviour are completely determined; on the other hand, the individual can just as easily be thought of as a free thinking, free acting and creative subject whose actions and behaviour are determined by his/her own personal inner drives and desires[17]. This is one of the most fundamental assumptions of Western culture and thinking.

This dualistic concept has pervaded in architectural design theories, which is as old as the history of design. It is found in the history of architectural styles and design practice as well as in academic theory, for example, between the Gothic and the Renaissance or between the Rococo and the Baroque style. And, it is also observed in CAAD research.

The below list (table 2-1) shows the dichotomies used in this thesis in order to explain designing, the teleology of computers, cognitive source and thinking modes.

[iii] The discussion on the mind-body dualism in designing and design studies has been already made by R.Coyne and A.Snodgrass, 'Is designing mysterious? Challenging the dual knowledge thesis', *Design Studies*, 12/3, pp. 124-131, 1991.

Table 2-1: A list of the dichotomies used in this thesis.

Category	Design as Science-like View	Design as Art-like View
Objective of Activity	To Discover Facts	To Create Values
Design Process	Systematic (Analytical) Process	Creative (Synthesis) Process
Design Thinking Type	Logical, convergent and rational thinking	Subjective, divergent and intuitive thinking
The View of Computer	Computer as Intelligent Tool	Computer as Visualising Tool
Cognitive Source	Knowledge	Imagery
Mode of Representation	Propositional Representation	Pictorial Representation
Neurological Analysis	Left Hemisphere Dominance	Right Hemisphere Dominance

Each concept is applied as a polar opposite: the one as subjective, idiosyncratic, and irrational, the other as objective, systematic, analytical and rational. That is, the rationalistic viewer regards design as a searching process for an objective fact out there somewhere, and the other as a creative activity involved in the designer's inner world. Dual theory identifies design thinking as two different cognitive styles - logical, analytical and rational on the one hand, and subjective, idiosyncratic and irrational on the other[18]. They are often distinguished as intelligence/creativity or convergent/divergent thinking[19].

In CAAD research, while the former considers computer as an intelligent tool and focuses on design knowledge, methods or rules, the other views computer as a design tool and prefers to take imagery, intuition or creative thinking as the cognitive design source. In cognitive psychology, the representation modes of thinking are distinguished as propositional and pictorial representation[20], which will be discussed in the chapter 5. More physical evidence of this dualistic concept has been demonstrated through neurological analysis, which reveals that the typical modes exist in the left and right halves of our brain that are characterised respectively as analytic-synthetic, linear-holistic, serial-parallel or focal-diffuse[21]. Such dichotomies are captured by the literature review of many fields related to this thesis, which will be discussed more precisely throughout the following chapters.

2.2.4 Beyond Dualism: Design as a Discipline in its Own Right

The word 'art' and 'science' seem to imply an exclusive duality, in which design can only be either art or science. Even though the dual structure is capable of supporting a design theory, each cannot explain all of the phenomena of designing, and makes it difficult to define holistic design. Designing is clearly neither a scientific endeavour nor an artistic work; its role is neither solely to understand and describe a fact nor merely to express ideas and values. Rather, design may lie somewhere on a continuum between the extremes in their purest conceptions.

Jones (1979) pointed out that this split view in design theory has become the main obstacle to understand design, and it results from the separation of the rational from the intuitive, the practical from the creative[22]. Thus, to understand the nature of design, we must at least acknowledge the variety of design activities and need a comprehensive viewpoint including the properties of art-like and science-like interpretations.

Historically, the architect has been regarded as a hybrid profession, artist and a functional specialist. While the former see the architect as a creator of forms constrained by the demands and the limited resources of his client or patron, the latter sees the architect as a specialist bringing design competence and special knowledge to the fulfilment of individual and social needs[23]. Thus, the architect as good designer must be as rational as possible, yet must also exhibit intuition, imagination and fantasy[24], and then must preserve not only the ability to realise creative potential, but also the accumulated knowledge to solve a specific problem in situation.

Design is therefore neither art nor science but a synthesis of the two. Otherwise, it may be something more than the sum of two. Design is just design, and design should be explained as a subject in its own right. Archer (1979), in this context, argued that the design discipline as a 'third area' different from Science and the Humanities, which is the area of human experience, skill and understanding that reflects man's concern with the appropriation and adaptation of his surrounding in the light of his material and spiritual needs[25].

In sum, design is both art and science, or more than both. It therefore becomes a multi-disciplinary subject: its scientific approach, methods and material culture would derive from Science; its history, its philosophical and critical ideas would belong to the Humanities; its aesthetic taste, sensibility and skills would come from art or craftsmanship[26]. Thus, design discourse (such as on the computability of design) cannot avoid the influence of other neighbour fields: Science, Humanities, or Art.

Conversely, such an amalgamative research environment has provided an impetus for design studies to achieve its own voice, languages or knowledge in their theories, and to establish design as a discipline on its own ground. From this observation, this thesis explores and examines both territories of art and science in design in order to establish an inclusive CAAD design theory.

2.3 Design as a Problem-Solving Process

People are faced and deal with many problems in every day life and so naturally are involved in a problem-solving activity. But, not all-everyday problems are included in this category. Problem-solving is generally regarded as 'any action taken by a person in pursuit of a blocked goal, whether physical or mental[27]'. That is, the tasks of problem solving have their goals and reasons to act; they require *conscious* mental activity. The activity of problem solving begins with realising what is wrong or unsatisfactory. Any problem consists of the existing status (the condition) and the desired goal; between them, there must be a discrepancy that the solver will remove with some means and strategies. Of course, its execution appears to involve some intelligence.

From this respect, design activity can be seen as a series of conscious actions for eliminating the misfits between an existing situation and design goals, using knowledge and experience; that is, a conscious problem-solving activity. As a result, this total event is seen as one of information processing.

Historically speaking, the modernists, since the modern design movement, began to speak of architecture as a 'problem-solving' activity; that is, in a given set of technical, economic or social conditions, the architect finds the perfect, functional solution[28]. Since then, along with the development of information theories and the computer, the framework of design as problem-solving or information-processing has been frequently employed in deploying (architectural) design theories and CAAD. It has allowed the scientific examination of designers and design problems, and further has provide a useful reference to design computation. Consequently, most CAAD researchers have taken this paradigm as the crucial medium to conceptualise and model designing; and as theoretical framework for computerising design activities.

2.3.1 The Problem-Solving Paradigm[iv]

Polya (1962) asserted that 'solving problems' is a specific achievement of intelligence that consists of the gift of mankind and the important element in the development of civilisation[29]. The human engages in such conscious activities, raging from the puzzle problem to theorem-proving. In this sense, designing also can be seen to belong in the problem-solving paradigm, similar to other sorts of intellectual activity.

Information-Processing Mechanism in the Problem-Solving Process

The problem solving theory was developed from the attempt to understand how people solve problems and to improve human performance. Further, Newell and Simon's theory focused on the computer's role in the problem-solving process and they made the first attempts to build an intelligent computer by simulation programs[30]. Since then, much research related to human or computer problem-solving, like computer science, cognitive science, or cognitive psychology, has shared this problem-solving paradigm.

The process of solving a problem is generally accepted as a series of processes, which include encoding information from the environment, retrieving information or knowledge from long-term-memory and transferring that information in some way. Thus, it is often equated with information processing in the human mind and it is analogised as an information system consisted of input, processing and output processes.

That is, the problem-solving systems posit the situation like this: *input* captures or collects raw data from the external environment, *processing* converts this raw input

[iv] The definition of paradigm was suggested by Kuhn, as a framework of concepts, results and procedures within which subsequent work is structured and an open-ened resource is provided. Quoted by S. Blackburn, *The Oxford Dictionary of Philosophy*, Oxford University Press, Oxford, 1996.

into a more meaningful form, and then *output* transfers or activates the processed information[31]. Meanwhile, in cognitive psychology, these mental operations are identified as the information-processing mechanism like 'sensory store-(filter)-recognition-(selection)-short term memory-longterm memory process'[32]. In this way, the information-processing mechanism involved in human problem-solving activities has offered lots of opportunities in computerising human functioning.

Problem-Solving Strategies

General problem-solving theory hypothesizes that even though they bay be in different domains, all problems can be explained with the same terminology such as problem space, initial state, goal state, operators or strategies, and they share the similar solving-processes and strategies. Newell and Simon (1972) explained general problem-solving behaviour as follows:

> When a person is confronted with *a problem*, it implies that certain information is given, that is, about what is desired, under what conditions, by means of what tools and operations; and then this information is interpreted by the problem-solving agent[33].

Thus, problem-solving behaviour usually is defined as a selection among information that best achieves the desired goal or a search from an initial state to a goal state through information process and each state is a candidate solution (or partial solution). Applying a finite sequence of operations effects transitions from one state to another. Thus, the problem solver's task is to find a path from some initial problem state to a solution state or to find an operation that results in a state that is on the solution path. All these actions take part in a *problem space* as resource for potential solutions in computer systems. This problem space may be represented symbolically with data, goals, operators and so on.

However, not all of the problems are well-defined problem with clear beginning and ends, and the majority of human problem-solving effort is directed toward ill-defined problems, which defy complete description and lacks the clarity of formulation[34]. With reference to this, Simon (1973), in '*The Structure of Ill-Structured Problems*', asserted ill-structured problem (ISP) as a residual concept; that is, the boundary between well-structured problem (WSP) and ISP is a vague and fluid boundary. He argued that ISPs can be successfully tackled in the way to split up hierarchically into desirable sub-WSPs and thus distinction between IPS and WSP may be nothing more than the respective sizes of knowledge base[35].

However, such ISPs have typically huge numbers of alternatives and consequences at each step, and they do not lend themselves well to an algorithmic solution. Thus, it is impossible for them to be tackled with the conventional general problem-solving strategies. Naturally, the awareness of limits of general problem-solving has led the research concerns to domain problems, domain specific knowledge and heuristics.

The strategy of heuristics - rules of thumb- was introduced to search for a solution in the potentially huge space of possibilities or to avoid the combinatorial explosion of alternatives. It is a control structure that can guide the search or to provide valuations. In this search process, the technique will explore only some of the possible alternatives, and will apply its valuation heuristics in the absence of full knowledge.

Well-known general heuristics in AI, such as forward and backward chaining, means-ends analysis fall within this category. Forward chaining is a searching technique from facts to the conclusions which follow from the facts; backward chaining is a searching from a hypothesis back to the facts which support the hypothesis; mean-ends strategy is choosing the means that will bring problem-solver most quickly to that end or goal, which depends on an achieved classification of recurring patterns of events[36]. In parallel with heuristic strategies, a number of the operational models, whether they are conducted primarily by humans or by computers or both, has been suggested for ill-structured problem-solving: for example, Newell's 'Generate-And-Test[37]' method; heuristic search MEA (means-end-analysis)[38]; 'Propose-Critique-Modify[39], and so on.

Knowledge in the Problem Solving Process

Rationality is a kind of behaviour to be described as rational. To accept something as rational is to accept it as making sense, as appropriate, or required, or in accordance with some acknowledged goal, such as aiming at truth or aiming at the good[40]. The rational tradition has been a mainspring of Western science and technology, and has demonstrated its effectiveness most clearly in the science, whose principles can be captured in formal systems whose highest expression lies in mathematics and logic[41].

Problem-solving paradigm has a shared value with the philosophy of science, such as objectivity, rationality and universalism[42]. In order to find a perfect, functional solution in given any condition, the solver behaviour is seen as a consequence of rational choosing among alternatives through the objective evaluation of outcomes. In doing so, they must be able to predict and evaluate consequences of anticipated action, and even consequences of consequences.

This process is performed through common strategies for design problems, such as decomposition, analysis, and evaluation. The perception of the problem starts with the grasping of well-known structural features, and then employs analysis in reducing a problem to systematic sub-problems that can be handled, with each level being more specialised and intelligible. Classification, hierarchy and category are the usual strategies employed in analyzing complex problems, and also help to organise related ideas into a structured group as a unit[43]. The unit contains knowledge about properties of a class of design elements as well as knowledge regarding the relationship between classes. In this way, these rationalistic strategies allow us to understand complex things; help us to discover new things and to link to our existing knowledge.

Accordingly, in the rational approaches to problem solving processes emphasis is predominantly on clear reason and knowledge rather than experience as problem-solving sources. Gelernter (1995) argued this as follows:

> "The rationalists claim that while objective knowledge originates in and refers to an external world, that same knowledge is also somehow prefigured in the structure of mind...(so) it is more reliable to turn in on the mind and to use introspective reasoning for discovering there the world's essential knowledge."[44]

In this context, the complete knowledge and information should be externalised and pre-structured in order to resolve problems – that is, the objective and universally valid knowledge that exists independently of individual experience. In addition the clear knowledge, the rational tradition in problem-solving centres on a rational process. It assumes that human behaviour can be operated with full knowledge of what the person is doing and why they are doing it; problems can be entirely explicable by dividing them into separate constituent parts; and hence, the solution can be generated by assembling the constituent parts.

However, these rationalistic Cartesian legacies in the problem-solving paradigm, such as mind-body dualism and the atomic concept, have been criticised by many theorists discussed to human and computer. For example, Dreyfus (1972, 1993) in philosophy[45], Winograd and Flores (1986) in cognitive science[46], Coyne and Snodgrass (1993) in CAAD[47] have opposed the rationalistic view of computer and human by taking Heideggerian perspective in philosophical thinking. Their arguments will be introduced throughout the following chapters.

2.3.2 The Characteristics of Design Problems

In the problem-solving paradigm, design is regarded as information processing that consists of amounts of problem-solving activities, transferring a design problem into a solution by applying operations. That is, the designer starts with information about a client and ends with information about a building that may be somehow fitting with the client's information.

Designing usually starts by defining a set of problem constraints between the desired objective and the given real situation. In this process, the design problem is issued as a barrier to achieving a goal or as the undesirable condition requiring action to remove it[48]. As the designer recognises the constraints, misfits or unsatisfactory condition in given situation, they become highly problem-concious.

Design constraints include social, cultural, environmental or designer's personal constraints[49], and they affect both the information considered and the results as well as their evaluation before any design problem is solved. In addition, these constraints limit the designer's endless fanciful imagination; in turn, it gives the designer clarity and certainty in a complex context. Accordingly, contrasting with fine artists, the designer may well feel rather comfortable and accustomed in dealing with them than working without them.

However, the designer cannot start with complete information from the beginning. As design is processing, the constraints become clearer, new constraints are sometimes evoked. This is because the design problems themselves contain solutions that the designer must achieve[50]. By this what is meant is that design problems defy complete description and its structure lacks the clarity of definition. Moreover, there is no definitive formulation; there is no definite criterion; and there is no problem space defined in any meaningful way for design problems. In this sense, Schön (1985) points out the characteristics of the design problem faced by practicing designer as a condition of *complexity*, *uncertainty* and *uniqueness*[51].

Likewise, designing must have very different characteristics from other problem-solving processes, to some degree even though sharing the rationalistic aspects with this paradigm. Rittel (1995) asserted that all design problems are wicked, ill-behaved problems but to varying degrees problems, compared to tame, well-behaved problems[52]. He, along with Webber (1973), suggested the 'ten characteristics[53]', which distinguish the design problem from one of science or mathematics. It becomes a consensus that most of architectural design problems are ill-defined, ill-structured, or wicked.

2.3.3 Design Problem Solving Process

Wade (1977) stated, in *Architecture, Problem, and Purposes*, that any design problem solving process has two kinds of information - demand and supply information. The former includes the design goals and the requirements of users, clients or regulations; the latter includes a given cultural, social, environmental situation[54]. In this process, when the conflicts between demand and supply appear, a design problem is issued and the designer starts to search for an acceptable solution in a particular design context. That is, any design activity entails choices among the possible alternatives for a solution that meets the requirements. Accordingly, like any other problem-solving activities, the design process is considered as a continuum of selection or decision-making. Design in this paradigm, is generally called a goal-oriented *searching process* or *exploratory process*.

Design as a Searching Process

The design process is often regarded as a searching activity among the alternatives for a solution that is satisfying the design demands. This design model was constituted of a set of a problem, a criterion of solution and a formal algorithm for searching it. In the computer system, they are replaced with an initial state, a goal state, and operators. Bench-Capon's (1990) notions show a typical searching process as follows:

> "We are given an initial state and a goal state, together with a set of operators which, when applied to a state in the search space, will return a different state in the search space. The problem is therefore to find a sequence of states which will lead from the initial state to a goal-state, and where each state can be reached from its predecessor by the valid application of an operator.[55]"

Thus, the searching techniques were at the central issues of AI systems or theories; that is, how to find out the desired route from an initial state to a goal state without generating more of the search space than necessary. For example, goal-driven (forward reasoning) and data-driven search (backward reasoning); breadth-first and depth-first searches[56] are well-known strategies employed in AI systems.

However, these systematic search methods seem not to be amenable to true design problems, which are relatively complex and ill-defined to be addressed by logical methods. Thus, another method for ill-defined problems is introduced from AI, namely, *heuristics*. This refers to rules of thumb that the human problem solver usually uses to tackle a real problem. Heuristics are based on the fact that much of human knowledge is based on empirical knowledge gained from experience[57]. Though this method is not bound to succeed in design systems, it provides valuable shortcuts that can reduce time and cost in search process. In other words, when the problem space is arbitrarily large and uncertain, heuristics are used to control the extent of the search and thereby help an economical convergence to a goal state.

Design as an Exploratory Process

Another way to view design as a problem-solving activity is to regard designing as an exploratory process. Design is typical of an ill-defined problem solving process, in which procedures and solutions cannot easily be understood and anticipated in advance. There are a number of possible solutions open in design, and the designer discovers what is an acceptable solution to the problems by proposing solutions. That is, in the open-ened design process, there are no definite design solutions, even after the design is complete. As a result, the problem space becomes even larger and more unmanageable. Design is therefore more than a searching process toward a solution.

Parallelled with the ill-structured nature of design problems, what makes design problem space more complex and more massive is the unstableness of the design processes. As the problem space transforms other stages or progress towards more particular design, another misfit or new problems are evoked in design space. Thus, design is developed together with the gradual refinement of early conjectures. The possible solutions may be continuously evaluated, modified, and then chosen until the designer feels satisfied. This exploratory process pushes the designer toward a refinement of existing solution, and leads the designer to discover a new solution. In this process, both problem and solution often emerge together rather than one logically following from the other[58]. That is, both problem and solution become clearer as the process goes on.

Lawson (1979) characterises this as a 'solution-focused' process, as opposed to the 'problem-focused' of the scientist's activity as, in that the architects tackle design problems by proposing solutions to them[59]. In this way, the designer can discover more about the problem and what is an acceptable solution to it. Thus, this exploratory process should be a learning process from its solution as well as its own problem. In the similar vein, Simon (1973) classes the modification in problem space as *adaptation* and *learning*: if the continuing alteration of the problem representation is short-term and reversible, it is called adaptation or feedback. If the alternation is more or less permanent (e.g. revising the laws of nature), it is referred to as 'learning'[60]. In this regard, Gero (1990) also prescribes the design activity as a goal-oriented, decision-making, exploration, and learning activity that operate with a context[61].

In this way, the designer presents a solution in problem space only as assumptions, conjectures or alternatives that imply not what ought to be, but what may be possible, and they continually modify the initial goals and solutions through mutual trade-offs. Thus, design problem space in each stage becomes, literally, a space of possible design states and an arbitrary or dynamic milieu rather than static or linear. These features of problem space change the design process from a problem-fixing process into a less controllable, more divergent direction.

Accordingly, these characteristics of design problems and design process - the ill-structured and the unstable - have held back attempts to concoct a problem-solving design model or a problem-solving design system by formalising designing in terms of rules, cause-effect relationships, or knowledge that can control operations and transitions to solve design problem. In the next section, I will present three design models under the umbrella of the design problem-solving paradigm, which have been the main streams in explaining design.

2.4 Three Design Models in the Design Problem-Solving Paradigm

Design modelling is a research endeavour that attempts to illustrate the sequence of the activities performed during the design process, and it represents how design is (or may be) carried out. It aims to control the design process more efficiently to produce a fast, reliable design activity. Over the years, many design models have been proposed with the hope that being employed (1) in performing in practicing design tasks; (2) in applying new design methods, technique and systems; or (3) more recently, to mimic design activities in a computer model. There has been a dominant paradigm in theses design models; that is, design process consists of a series problem-solving activities within information processing mechanisms.

Dixon (1988) has classified design models as three characteristic types: prescriptive (what should be done); cognitive (what is done); and computational (how to do it) models[62]. In addition, Sivaloganathans *et al.* (1995) develop this idea and propose four categories: (1) prescriptive design models based on the design process; (2) prescriptive design models based on product attributes; (3) descriptive design models; and (4) computational design models. According to them, while the prescriptive design models focus on prescribing how the design process ought to proceed, the descriptive models emanate both from the experience of individual designers and from studies carried out on how designs are created[63].

Instead, I will present three kinds of design models under the design problem-solving paradigm – systematic three-step design models; knowledge models; and cognitive models. These categories are classified by the associated theoretical development, especially, in the light of the computational models for architectural design. That is, the early design models were committed to simplifying the design process into an algorithmic and systematic procedure that encouraged designers to adopt improved ways of working. Meanwhile, as the computers have come into wide use in designing and the study of CAD became integral with design science[64], this systematic model gave way to the new information-processing models that are more amenable to working with computer systems. More recently, the computable design models have evolved into a cognitive model that focuses on the designer's cognition.

2.4.1 Systematic Three-Step Design Models

Since the early of 1960s when the Design Method Movement started, design researchers have concentrated on the efficiency of design process. Their research was originally founded on the rational, systematic view that was stemmed from operation research (O.R), and they were concerned with systematic approaches, scientific methods, and logical operation for designing[65].

The first models of design process belongs to this systematic design model – namely, the three-step design model, which describes design as a sequential and recursive process of analysis, synthesis and evaluation. These models were proposed with more and less the same central ideas, which consisted of a problem being stated, then followed by analysis, then a solution being synthesized and evaluated. Thus, before generating a design solution (synthesis), understanding and analysing a problem are enacted, and then this solution is tested or evaluated with some prescribed criteria. This cycle is repeated until a level is completed by the acceptance of one or more of the evaluated potential solutions and then attentions move to the next level of the total problem.

Flowing from these ideas, many systematic design processes were proposed. For examples, Jones (1963)[66] and Luckman(1984) [67] proposed the best known three stage process of analyses-syntheses-evaluation, and other design theorists followed this approach[68]. In addition, Asimow (1962) used six design stages: analysis, synthesis, evaluation and decision, optimisation, revision, and implementation[69]. Even the Royal Institute of British Architects (1965)[70] reinforced this view of design by prescribing design process as a sequence of 'assimilation-analysis-synthesis-evaluation-communication'. Most of these restructured design systematic processes were some derivatives of the three-step model proposed in the form of a linear flow chart or two-dimensional structure[71].

These systematic models have a considerable commonality of the Cartesian view of Science[72]. That is, design problem-solving process is performed by breaking a design problem down into sub-problem, and solving each of these separately with design methods and then synthesizing solved sub-problems. In this context, before solutions are sought, design process or design problem must be subdivided into their constituent parts or aspects in which their properties, variables, strategies and criteria are fixed or known in advance. In this sense, designing is seen as a natural phenomenon that has some regularity in recurring pattern and can be predictable and can be represented in forms of knowledge or design methods.

Likewise, the early design models consisted of a set of step-by-step activities that could be systematically manipulated by a series of design methods or by design systems. In this context, the designer's role is very much that of a human computer who operates only on the information that is encoded and follows through a planned sequence of analytical, synthetic and evaluative steps and cycles until the best of all possible solutions is recognised. However, these attempts to restructure the systematic design process on the base of the scientific methods and techniques of problem-solving could be hardly applied in design practice. There is no doubt that the complexity, the idiosyncratic and other innate characteristics of designing would hamper the establishment of an all-compassing and widely accepted systematic design model.

2.4.2 Knowledge Models for Design

As the systematic design models proved to be less applicable to designing, and as AI was introduced in the design field, knowledge models have emerged, which are more open to working with computer systems. These knowledge models are represented by a logical diagram or a computer program of the way in which information flows and operates in a designing situation. They have usually borrowed many basic ideas, strategies and technologies from artificial intelligence.

In contrast to the early systematic, algorithmic models, knowledge models are oriented to solving ill-defined problems, by exploiting the strategy of heuristics. Heuristics are a knowledge used to make good judgements, or the strategies, tricks, or 'rules of thumb' used to simplify the solution of problems[73]. Heuristics are usually acquired with much experience. This type of reasoning may not always be correct, but it frequently is, and when it is it leads to a quick solution. Thus, these models have adapted many strategies from AI in order to tackle designing as a heuristic searching or an exploratory process.

In this model, the problem-solving activities were supposed as a series of conscious behaviours involving human or computer's intelligence. Human intelligence counts upon a variety of capabilities, including reasoning, understanding, learning; knowledge and experience. As a typical ill-structured problem, the design task requires a large problem space, retains many possible constraints and alternatives, and hence it is involved in various intelligent activities. Thus, design problems become to need large amounts of domain knowledge that can be brought to bear at each step.

Design knowledge is usually categorised into the design itself, the rules that apply in the context, and information about the design[74]. They can be employed in design problem-solving with various forms; that is, knowledge may help the designer to generate solutions; some may transfer data into useful information; or some validate design conjectures.

This model is derived from the observation that the specialised expertise of architects can be organised as a set of knowledge of how to achieve useful results, and that the computer can store and manage such huge amount knowledge. In this way, these models have been to some extent successfully implemented by some intelligent design systems, such as expert systems or knowledge-based design systems, in which design knowledge can be captured by, for instance, devising shape grammars or design rules specifying *if* and *then*[75].

2.4.3 Cognitive Models

The previous two design models have been employed in the design principles, grammar, logic, or production systems that can apply mathematical formalisms or knowledge-based technologies directly to design. However, they have so far only captured routine or repetitive design and do not support the typical complex design process in a fundamental way[76]. Consequently, design research has come to differentiate the design problem solving from other problem solving activities[77]. Researchers have come to identify the unique, significant aspects in the design process and hence, they have turned their interests to the designer's thoughts and the mental operations that are the internal representations and processes of design cognition.

Naturally, their concerns have turned to cognitive psychology and cognitive science, in order to seek appropriate models. Cognitive science research has sought not only a design model that can provide the understanding of mechanisms in design and the several characteristics of a man-machine interface via simulations of designer-computer systems, but also for a potential theoretical basis in building design computational models.

The Studies on the Design Cognitive Process

The definition of 'cognition' varies with each field's viewpoint, ranging from the acquisition of knowledge, 'the essence to all human intelligent activities'[78], broadly to 'all of human thinking activity'[79]. This thesis takes the meaning of cognition simply as the acquisition and use of knowledge involved in the problem-solving process. The objective of cognitive analysis is to understand, formalise and model the cognitive processes in the sequential development of design.

In order to capture the design cognitive process, design researchers have employed the investigation methods borrowed from cognitive psychology: for example, protocol analysis, interviews, or introspection on sketch design[80]. Among them, protocol analysis is a general method in the design cognition research, which can be described as 'talking aloud' during designing. Akin's '*Psychology of Architectural Design* (1986)' was one of the most crucial works in proposing a model of the cognitive process in the architectural design problem-solving domain. He used protocol analysis as an observation technique employing verbal descriptions of design thinking[81].

Akin's protocol analysis had much influence on later design enquiry and has produced very rich data that carry the intrinsic interest of reflections on real-world designing. Despite criticisms that talking aloud may distort normal thinking, and inevitably ignores the unconscious processes that lead to sudden insights, reliance on verbal protocols is still the most common method for observing problem-solving in action[82].

In addition, the growth of research significance found in design cognition studies has resulted in an increased development of computational models in artificial intelligence, which are founded upon cognitive processes[83]. Thus, the studies of design cognition and computation become an integrated research field.

Cognitive Computer Models

The basic assumption in cognitive modelling is that humans are processors of information, and that human thinking can be explained by means of the information processing mechanism. Human beings, therefore, are treated as an information processing system, that is, a computer. Such design models attempt to capture the essence of the designers' cognitive processes, and to explicate the principle of their operations. Oxman and Oxman (1994) articulate the key issues of design cognitive models like this:

> "The identification of cognitively significant structures of knowledge; the structuring of knowledge into chunks and their organisation in memory; the representational content of cases, problems of indexing, search and retrieval of relevant prior solutions; and the development of techniques for re-use and modification of cases.[84]"

Meanwhile, Coyne and Snodgrass (1993) view computation as just one of many metaphors we have at our disposal for understanding design; and this metaphor is not here considered linguistic devices for communicating thoughts but devices for shaping our thinking and action[85]. In this regard, cognitive modelling is not only employed as a basis for experimental research through the study of behaviour, but also as a tool for building of the theoretical foundations of design cognition though computational modelling of design processes and reasoning.

Oxman and Oxman (1992) identify the prominent two cognitive approaches to design models: (1) refinement, or model-based generic design, and adaptation, or (2) case-based, adaptive design[86]. These models employ more advanced technology and more sophisticated cognitive strategies than rule-based models, from the theories of cognitive science and cognitive psychology. Based on these design models, CAAD research has recently yielded many design systems such as generic systems or case-based systems[87].

2.5 Discussions

In CAAD research, designing is usually understood in terms of the problem-solving process in which the designer transforms a design problem into a solution by applying operations. However, since the design problem is characterised as an ill-defined problem, there are no definitive formations and no right or wrong answers in design, but only better or worse ones[88]. In parallel with the nature of ill-structured problems, the design process is involved in a satisfying rather than optimising behaviour[89], and in a dynamic exploratory process rather than a static selection or a search process.

In addition, designers attend simultaneously to many levels of design phases, and also use simultaneously various kinds of knowledge; not only the knowledge that can be represented by explicit terms, but also intuitive, tacit knowledge, knowledge derived from action as well. From here, a suspicion is emerged whether design can be explained by the problem-solving paradigm, information processing or cognitive process; and whether design solutions can be generated by a series of rules, grammars, or design knowledge.

Even though design problems certainly involve some intelligent problem-solving activities, the idea seems to be incomplete to explain design itself or the design process. Furthermore, even though design cognitive process is important to understand how the designer thinks when solving design problems, it is true that the design process strays sometimes beyond the designer's cognitive abilities. Thus, even though the problem-solving paradigm provides the crucial tools for computerising design, there is no design system that can solve design problems in a real design or a high-level design phase.

Those are the reasons why a new paradigm and theories are required in design domains. However, while it is easy to criticise the existing theory, it is not easy to establish a new theory. Especially, when it comes to the theory for the computer systems, the difficulty will increase, because any theory and technology for design systems is interrelated with other fields such as computer science, AI, or cognitive science. That is, their theoretical patrimony has much influence on establishing a CAAD theory, and their advanced technologies also have much influence on developing design systems. Accordingly, CAAD researchers could not easily leave behind the rational information-processing paradigm.

A new approach to CAAD, therefore, means to challenge the rationalistic traditions underlying in the information-processing paradigm. To do so, I will examine first the existing CAAD systems ranging from commercial applications to on-going research systems, and will review the teleology, technologies and theories exploited in design systems in the next chapter. This review is intended to comprehend how the problem-solving paradigm is employed in design systems; to investigate the predictions and limitations of this paradigm; and finally it can help to establish a new design model and a new theoretical paradigm for meditating a computer system.

Reference

[1] Simon, H.A., *The Sciences of the Artificial* (2nd ed.), MIT Press, Cambridge, 1981, quoted by S. Dasgupta, 'Herbert Simon's '*Science of Design*': Two decades later', in *First International Conference on Intelligent Systems Engineering*, Heriot-Watt University, Edinburgh, p. 171, 1992.

[2] Potter, N., *What is a designer: Things. Plan. Messages,* Hyphen Press, London, p. 13, 1989 (3rd ed.).

[3] Willem, R. A., 'Design and science', *Design Studies,* Vol.11, No.1, pp. 45, 1990.

[4] Hawkes, D., 'The technical imagination: thoughts on the relation of technique and design in architecture', *The Journal of Architecture*, Vol.1, winter, pp. 335-346, 1996.

[5] Dilnot, C., 'Transcending science and 'anti-science' in the philosophy of design method', in *Design: Science: Method,* R.Jacques, and J.A.Powell, (eds.), Westbury House, pp. 112-116, 1981.

[6] Larson, M. S., *Behind the Post-modern Facade: Architectural Change in Late Twentieth-Century America,* University of California Press, Berkeley, 1995.

[7] Ibid., pp. 4-5.

[8] Gelerner, M., *Sources of Architectural form: A critical history of Western design theory,* Manchester University Press, Manchester, pp. 220-255, 1995.

[9] Schön, D., *The Design Studio: An Exploration of its Traditions and Potentials*, RIBA, London, 1985.

[10] Lawson, B., *Design in Mind,* Butterworth-Heinemann Ltd, Oxford, p. 6, 1994.

[11] Potter, N., 'Problems with method', in *What is a Designer: Things, Places, Messages, op. cit*, pp. 59- 76.

[12] Amstrong, D.M., 'Early Causal and Functionalist Views', in *Mind and Cognition,* W.G.Lycan (ed.), Blackwell Publishers, Oxford, p.37, 1990.

[13] The Concise Oxford Dictionary (9th ed.), Clarendon Press, Oxford, 1995.

[14] Gelerner, M., *Sources of Architectural Form: A Critical History of Western Design Theory, op. cit.*, pp. 122-127.

[15] Allinson, K., *The Wild Card of Design: A perspective on Architecture in a Project Management Environment*, Butterworth Architecture, Oxford, 1995.

[16] Franz, J. M., 'A critical framework for methodological research in architecture', *Design Studies,* Vol.15 No.4, 1994.

[17] Gelernter, M., *Sources of Architectural Form: A Critical History of Western Design Theory, op. cit.*, p. 27.

[18] Coyne, R. and A. Snodgrass, 'Is designing mysterious? Challenging the dual knowledge thesis', *Design Studies,* Vol.12 No.3, pp. 124-131, 1991.

[19] Hudson, L., *Contrary Imaginations*, Methuen, London, 1966, quoted by G.Broadbent, *Design in Architecture: Architecture and the Human Science*, David Fulton, London, 1988.

[20] Paivio, A., *Imagery and Verbal Process*, Rinehart and Winston, New York, 1971.

[21] Bradshaw, J.L. and N.C. Nettleton, *Human Cerebral Asymmetry*, Prentice Hall, 1983, quoted by M.Trovey, 'Thinking styles and modelling systems', *Design studies*, Vol.7, No.1, pp. 20-30, 1986.

[22] Jones, J.C., 'Designing Designing', *Design Studies,* Vol.1, No.1, pp. 31-35, 1979.

[23] Schön, D., *The Design Studio: An exploration of its Traditions and Potentials,* RIBA Publications Limited, p. 3, 1985.

[24] Rittel, H.W.J., 'Impressions of architecture 130', in *Design Methods: Theories, Research, Education and Practice,* Vol. 29 No.1, p. 2132, 1995.

[25] Archer, B., 'The Three Rs', *Design Studies.* Vol.1 No.1, pp.17-21, 1979.

[26] Ibid., p.19.

[27] Kahney, H., *Problem Solving: A Cognitive Approach*, Open University Press, Milton Keynes, p. 103, 1986.

[28] Gelernter, M., *Sources of Architectural Form: A Critical History of Western Design Theory, op. cit.*, pp. 250-254.

[29] Polya, G., *Mathematical Discovery (Vol.1),* Wiley, New York, 1962, quoted by S.K.Reed, *Cognition: Theory and Applications* (5th ed.), Books/Cole Publishing Company, Pacific Grove, p. 354, 1996.

[30] Winograd, T. and F. Flores, *Understanding Computers and Cognition: a New Foundation for Design,* Addison-Wisley Publishing Company, Inc., Reading, p.22, 1987.

[31] Laudon, K.C and J.P.Laudon, *Essentials of management information System*, Prentice-Hall International Inc., NJ, pp.5-6, 1995.

[32] Reed, S.K., *Cognition: Theory and Applications* (5th ed.), *op.cit.,* pp. 4-18.

[33] Newell, A. and H.A, Simon, *Human Problem Solving*, New York, Prentice Hall, pp. 72-73, 1972.

[34] Reitman, W.R., 'Heuristic decision procedures, open constraints, and the structure of ill-defined problems', in *Human Judgements and Optimality,* M.Shelly *et al.* (eds.), Wiley, New York, pp. 282-283, 1964.

[35] Simon, H.A., 'The structure of ill-structured problems', *Artificial Intelligence,* 4, pp. 181-200, 1973.

[36] Wade, J. W., *Architecture, Problems, and Purposes: Architectural Design as a Basic Problem-Solving Process,* John Wiley & Sons, New York, p. 57, 1977.

[37] *see,* Newell, A., 'Heuristic programming: ill-formed problems', in *Progress in Operations Research,* J. Aronofsky (ed.), Vol.3, Wiley, New York, p. 377, 1969.

[38] *see*, Simon, H.A., *Sciences of The Artificial* (1981), *see*, for the design application, Akin, Ö., 'Chapter 5: Search in design', in *Psychology of Architectural Design*, , Pion Limited, London, 1986.

[39] Chandrasekaran, B., 'Design problem solving: a task analysis', *AI Magazine*, pp. 59-71, Winter, 1990.

[40] Blackburn, S., *The Oxford Dictionary of Philosophy*, Oxford University Press, Oxford, p. 319, 1996.

[41] Winograd, T and F. Flores, *Understanding Computers and Cognition: A New Foundation for Design*, *op. cit.*, p. 14.

[42] Cross, N., J. Naugton and D. Walker, 'Design method and scientific method', *Design Studies*, Vol.2, No.4, pp. 195-196, 1981.

[43] Wade, J.W., *Architecture, Problems, and Purposes: Architectural Design as a Basic Problem-solving Processes*, Cambridge University Press, Cambridge, pp. 42-45, 1984.

[44] Gelernter, M., *Sources of Architectural form*, *op. cit.*, pp. 32-33.

[45] Dryfus, H. L., *What Computer Can't Do: The Limits of Artificial Intelligence*, Haper and Row, New York, 1972, and *What Computers Still Can't Do*, MIT Press, Cambridge, MA, 1993.

[46] Winograd, T. and F. Flores, *Understanding Computers and Cognition*, *op. cit.*

[47] Coyne, R., and A. Snodgrass, 'Is designing mysterious? Challenging the dual knowledge thesis', *Design Studies*, Vol. 12, No. 3, pp. 124-131, 1991 and 'Rescuing CAD from rationalism', *Design Studies*, Vol. 14, No. 2, pp. 100-123, 1993.

[48] Archer, L.B., 'The structure of the design process', in *Design Methods in Architecture*, G.Broadbent and A.Ward, Lund Hamphries Publishers Limited, pp. 76-102. 1969.

[49] Best, G., 'Method and intention in architectural design' in *Design Methods in Architecture*, G.Broadbent and A.Ward, Lund Hamphries Publishers Limited, pp. 147-165, 1969.

[50] Lawson, B., *How Designers Think*, Butterworth Architecture, London, pp. 81-91, 1988.

[51] Schön, D., *The Design Studio: An Exploration of Its Traditions and Potentials*, RIBA Publications Limited, London, p. 5, 1985.

[52] Rittel, H.W.J., *op. cit.*, pp. 2130-2135.

[53] Rittel, H.W.J. and M.M. Webber, 'Dilemmas in a general theory of planning', *Policy Sciences*, Vol. 4, pp. 155-169, 1973.

[54] Wade, J.W., *Architecture, Problems, and Purposes: Architectural Design as Basic Problem-Solving Process*, *op. cit.*

[55] Bench-Capon, T.J.M., *Knowledge Representation: An Approach to Artificial Intelligence*, Academic Press, London, p. 42, 1990.

[56] Patterson, D.W., *Introduction to Artificial Intelligence and Expert Systems*, Prentice-Hall International, Inc., pp. 167- 187, 1989.

[57] Giarratano, J. and G. Riley, *Expert Systems: Principles and Programming*, PWS-KENT Publishing, Boston, p. 8, 1989.

[58] Lawson, B., *How Designers Think*, Butterworth Architecture, London, p. 89, 1988.

[59] Lawson, B., 'Cognitive strategies in architectural design', *Ergonomics*, Vol.22, No.1, pp. 59-68, 1979.

[60] Simon, H. A., 'The structure of ill-structured Problems', *op. cit.*, p.160.

[61] Gero, J.S., 'Design prototypes: a knowledge representation schema for design', *AI Magazine*, winter, pp. 27-36, 1990.

[62] Dixon, J.R., 'On research methodology towards a scientific theory of engineering design', in *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM)*, Vol.1 No.3, 1988.

[63] Sivaloganathans, N.F.O., A.J. Evbuomwan, and H.P. Wynn, 'Design function development - a design system for thc future', *Design Studies*, Vol.16 No.4, pp. 447-470, 1995.

[64] Cross, N., *The Automated Architect*, Pion Limited, London, pp. 25-28, 1977.

[65] Broadbent, G., *Design in Architecture: Architecture and the Human Science*, David Fulton Publishers, London, 1988.

[66] Jones, J.C., 'A method of systematic design', in *Conference on Design Methods*, J.C. Jones and D. Thornley (eds.), Pergamon, Oxford, 1963.

[67] Luckman, J., 'An approach to the management of design', in *Developments in Design Methodology*, John Wiley & Son, Chichester, pp. 83-98, 1984.

[68] *See* Best, G., 'Method and intention in architectural design', in *Design Methods in Architecture, op. cit.*, pp. 151- 157, 1968. Also *see* Wade, J. W., *Architecture, problems, and purposes, op. cit.*

[69] Asimow, M., *Introduction to Design*, Prentice-Hall, Englewood Cliffs, New Jersey, 1962.

[70] R.I.B.A., *Handbook of Architectural Practice and Management*, RIBA, London, 1965.

[71] see, Markus, T.A., 'The role of building performance measurement and appraisal in design method', *The Architect's Journal*, pp. 1567-1573, Dec. 1967.

[72] Losee, J., 'Theories of scientific procedure', in *A Historical Introduction to the Philosophy of Science*, Oxford University Press, Oxford, pp. 114-130, 1980.

[73] Reed, S., *Cognition: Theory and Applications (4^{th} ed.)*, Books/Cole Publishing Company, Pacific Grove, pp. 369-381, 1996.

[74] Fawcett, W., 'A note on the logic of design', *Design Studies*, Vol.8, No.2, p.82, 1987.

[75] Mitchell, W., 'Three paradigm for computer-aided design', *Automation in Construction*, No.3, pp. 239-245, 1994.

[76] Coyne, R.F. and E. Subrahmanian, "Computer Supported Creative Design: A Pragmatic Approach," in *Modelling Creativity and Knowledge-Based Creative Design*, J. Gero and M. Maher (eds.), Lawence Eribaum Associates, pp. 295- 296, 1993.

[77] See, Goel, V. and P. Pirolli, 'Design within information-processing theory: the design problem space', *AI Magazine*, pp. 19-36, Spring, 1989.

[78] Oxman, R., 'Cognition and design', *Design Studies*, Vol.17, No.4, pp. 337-340, 1996.

[79] Mayer, R.E., *Thinking, Problem Solving, Cognitive*, W.H. Freeman and Company, New York, p. 6, 1983.

[80] Galle, P. and L.B. Kovács, 'Introspective observations of sketch design, *Design Studies*, Vol.13, No.3, pp. 229-272, 1992.

[81] Akin, Ö., *Psychology of Architectural Design*, Pion Limited, London, 1986.

[82] Akin, Ö. and L. Chengtah, 'Design protocol data and novel design decisions', *Design Studies*, Vol.16, No.2, pp. 211-236, 1995.

[83] Oxman, R., 'Cognition and design', *op.cit*, p. 337.

[84] Oxman, R. and R.M. Oxman, 'Case-based design: cognitive models for case libraries', in *Knowledge-Based Computer-Aided Architectural Design*, G. Carrara and Y.E. Kalay (eds.), Elsevier, Amsterdam, p. 46, 1994.

[85] Coyne, R. and A. Snodgrass, 'Rescuing CAD from rationalism', *Design Studies*, Vol.14, No.2, p. 102, 1993.

[86] Oxman, R. and R.M. Oxman, 'Refinement and adaptation in design cognition', *Design Studies*, Vol.13, No.2, pp. 117-133, 1992.

[87] Kolodner, J.L. and L.M. Wills, 'Powers of observation in creative design', *Design Studies*, Vol. 17, No.4, pp. 385-416, 1996.

[88] Rittel, H.W.J. and M.M. Webber, 'Dilemmas in a general theory of planning', *op. cit.*, pp. I36-144.

[89] Simon, H.A., *Models of Man: Social and Rational*, Wiley, New York, p. 261, 1957.

Chapter
3

Computers for Architectural Design

Abstract: *This chapter examines the existing commercial and on-going research computer applications for architectural design. It investigates their uses, predictions and limitations; and reviews the teleology, technologies and theories exploited for computerising design. Finally, I will discuss two trends in the developments of CAAD, and present the new directions in CAAD research. This study will be based on understanding the computer's roles in designing, and further on establishing a new theoretical paradigm for mediating a computer system.*

CHAPTER 3: COMPUTERS FOR ARCHITECTURAL DESIGN

3.1 The Emergence of CAAD

The ultimate purpose of design studies is to provide the designer with more efficient ways to be able to deliver better designs more quickly. One of the most important events in design studies since Design Methodology Movement, was the emergence of computer-supported designing in the simple form of software that executes parts of design processes.

In the 1960s, computer-aided architectural design (CAAD) studies appeared through experiments and research holding with the strong belief in the possibilities of an automated design process, by combining systematic design methods with computer technology. Many advanced fields, such as new mathematics, statistics or computer science, had much influence on the earlier computation of design, but its roots lied in the systematic design methods, which had provided the foundation of knowledge on which CAAD research could build. Thus, the pioneers of CAAD programs began with facilitating the existing established methods into computer programs[1].

Naturally, the first successful use of computers was mathematical models, where large amounts of numbers and equations were easily managed. Examples include cost control, structural calculation, simple space allocation and circulation in building. The development of mathematical models and systematic design methods seemed to be the preparatory steps for computerising the design activities.

Actually, many scientific design methods were transferred to computer models; such as space need analysis, interaction and grouping analysis, spatial synthesis, and cost and environmental analysis models. These models dealt with mainly design analyses and evaluations in design activities, which could be implemented by algorithmic programming.

Later, the development of AI and cognitive science has led many CAAD researchers to focus on the computation of the design process. Their efforts may be the prerequisite steps for the entire design processes to be executed automatically, or at least efficiently, within a computational environment.

Parallelled with the enthusiasms to automate the design process, applying computers as a graphic tool to architectural design began with Ivan Sutherland's pioneering work in the 1960's. Further important works started in the early 1970s with the advent of the storage tube graphic display from Tektronix, and was boosted by the arrival of effective minicomputers such as the PDP-11 and the Prime 300[2]. Ever since computing power became commercialised and computers have been extensively employed in the design practice, many researchers have worked on programming the design process into intelligent systems, or applying advanced computer technologies to designing. Consequently, a number of papers on computer-aided design have emerged in design conferences and publications and CAAD became a major subject in its own right[3]. It seems that the enthusiasm for design methodology has become convergent with computer-based methods.

As a result, CAAD researchers have been concerned not only with the technological advances of computer science such as computer programming, database systems, and computer languages, but also with its theoretical framework that can accommodate designing with computer. That is, they required the more sophisticated theories than the earlier systematic design approaches. For this, many design studies - especially CAAD - have taken up their theoretical framework from information theories such as 'design as information processing' or 'design as a problem-solving process', which is amenable to computerising design.

3.2 The Developments of CAAD

As a common phenomenon in today, the strength of the computer industry has affected on the development of design research and practice. The improvements in hardware and software means that today every designer has access to a computer: most have at least a PC on their desk, and use CAD (computer aided design) software or other applications in their daily work.

Naturally, there is a great stress on the use of computers in the design process. Computing has become a recognised skill in the discipline of architecture, moving from the periphery towards the core of the design process[4].

The development of techniques in computer science and AI, therefore, has greatly influenced the direction of CAAD research and of developing design systems. In this section, I will examine the existing or on-going research applications for architectural design by classifying their teleology into three categories. Then, I will discuss two different trends in the development of CAAD and the new directions for the future design system.

3.2.1 Computers for Architectural Design

The dedication of the commercial software companies and academic CAAD research have led to certain design processes being reasonably well computed, such as drafting software, various representation applications, environmental analyses, and even certain solution generating algorithms. Of course, it is ideal that computers are used for the entire working environment consisting of these functions. However, most applications have different functionality for the partial roles in design process, Thus, they have been separately employed according to each role such as for information processing, for production or representation, or for solution-producing.

Schmitt (1997) classifies the different relationships between computers and architecture into three levels, such as computer as an instrument (or tool), as a medium, and as a partner[5]. Instead, I categorise the computer-uses in architectural design practice into *information processing tools*, *graphical medium* and *solution-generating tools*. Such a different teleology is followed by the different reference of computer's role, a particular theoretical and technical background, and a different computational environment. Based on this categorisation, I summarise the results of exploring the commercial and on-going research applications for architectural design as follows:

Computer as a Design Information System

A design information system is one that has been used to store, maintain, and retrieve efficiently the required information or applications for the design process. It includes data management systems, decision support systems or telecommunication systems.

The designer starts to collect information about the project from various sources, such as technical data, norms, standards, costs, site description, precedent designs and so forth. The designer then has to transform, structure, and retrieve this information for use at every design stage. This is a time-consuming task and becomes beyond the realistic capacity of manual information systems. To address this, the development of information management technology has integrated the related software and peripheral devices into the core of information systems.

The information system combined with CAD is referred to 'an integrated CAD environment[6]', or CAD-based information system. Such systems produce design information by mainly using CAD applications, word processors, and more recently, telecommunications or multimedia.

They provide not only design information but also the design aid applications such as evaluation software, cost calculation software or modelling programs. In addition, the increasing linkage of computers with telecommunications has brought the design workstation instant access to external information - for example, new material catalogues, new engineering techniques or other design sources.

The effective use of information depends on how data are stored, organised, and accessed. Naturally, the most important technique in information systems is the database management technique such as shared filing or multi-tasking - the running of several applications at the same time, without mutual interference[7]. A database management system is simply the software that permits an organisation to centralise data, manage them efficiently, and provide access to the stored data by application programs.

The most important role of information systems lies in making the best or a better decision within certain alternatives. Winograd and Fores (1987) define the decision-making support system as a computer application for enhancing human decision making by suggesting alternatives, predicting consequences, and pulling together the information that goes into decision making[8]. Accordingly, design information systems must provide an opportunity for the designer to have easy access to a database when they intend to make a decision. This database will be a collection of updated information and knowledge from a number of application and information libraries.

The ultimate aim of an information system may be the full automation of architectural design practices, using the advanced computer technology and artificial intelligence. However, given the nature of design problem, design information systems remain at a low level supporting and controlling information processes. Thus, automated information-processing design systems are so far at an early stage.

Computer as a Graphical Medium

Computers in design also have been used for drafting, modelling, presenting, editing and visualising design, through various CAD package applications, drafting and modelling software, or multimedia applications.

Design is typically a result of working in various drawing, such as plan, sections, elevation and physical models. The benefits of computer-aided drafting and representing have become powerful, as equipping new functionality; for instance, mass reproduction, layers, real-world scale, speed and feedback, drawing object library, intelligent drawing, and so on[9]. Among the applications for design, drafting software have been the most successfully employed in the majority of architectural offices. Accordingly, CAD is sometimes used to refer directly to the drafting or representation software packages, and CAD is then interpreted as Computer Aided Drafting.

Since the early 1980s when PC-based CAD arrived, there have been hundreds of CAD software packages on offer. Among them, Autodesk™ has gained a market leading position. The developments of commercial CAD applications by the large software firms have made computer-using design become much more common in design practice.

More recently, beyond those of conventional CAD systems, multimedia and virtual reality system (VRS) offer the designer new design representational tools. Multimedia can facilitate the integration of two or more types of media, such as text, graphics, sound, voice, full-motion video, still video, or animation into a computer-based application. The CD (Compact Disc)-ROM can provide a personal computer (PC) with the storage capacity for all those media, especially for photographic images that the architect uses much frequently for representation. In the near future CD-Roms are likely to be replaced by DVI (Digital Video Interface) that will be even more capable of handling graphic (memory intensive) data. Furthermore, the authoring function of multimedia enables architects to store amounts of useful information and to represent the products in various ways with minimal requirements for programming skills.

Another advanced design support is the technologies of 3D modelling and animations in real time. These technologies have endowed CAD systems with the capabilities of visualising, rendering, and simulating a design product. By changing between 2D and various perspective views, the designer can continually evaluate the spatial implications of design decision. They also can generate a virtual space of both inside and outside of building, so that the designer can walk through the designed world. These applications have already been employed to a limited degree in the design process as a tool for evaluating designed environments.

Nevertheless, the drawbacks of commercial CAD software is that has been marketed primarily for a single process; for a single user; and for the later stages of the design process. Moreover, whatever two-dimension or three-dimension software, it based on the precise primitive graphical elements, and the structured operations for a specific task; such a precise and less flexible procedure hampers the designer to represent and experiment design ideas or images in the mind.

Computers are most frequently employed as a stand-alone unit to serve the specific purpose of drawing production and manipulation within a single process, usually in the detailed design stage. As a result, despite their significant graphic power, most of today's CAD systems are little used for design in its pure sense, but serves only for computer aided drafting and for presentation of the completed design.

Computer as a Solution-Generating Tool

A design system can automatically generate solutions to well-defined design problems through inference mechanisms. The technologies of AI have provided the CAAD with new approaches to generating design solutions. Intelligent design systems such as expert systems, knowledge-based systems, and case-based systems are included in this category.

Mitchell, in 1977, anticipated the roles of computer for architectural design as follows:

> "A computer may be used in design for any one, or a combination, of the following purposes: (1) simply to store and retrieve data describing a design; (2) to

automatically generate solutions to well-defined problems; (3) to test potential solutions for membership of the goal; and (4) to perform all of those functions - a comprehensive computer-aided architectural design system.[10]"

At that time, CAAD researchers shared a common vision that such a 'comprehensive design system' could automate the entire design process, and regarded the computer as thinking machine that could have the intelligence to solve design problems. Thus, the earlier enthusiasts in CAAD research focused, mainly, on the quantified and well-structued problems such as location, circulation, environmental conditions and cost estimating. The related mathematical models combined with the systematic design process model were developed through experiments and academic studies, relieving the designer from some tedious tasks.

However, these systems were proved to be of limited applicability. The awareness that design would be less amenable to systematic processes and logical structures led their concerns to a practical theory for CAAD or to the sophisticated technologies in terms of its usefulness for design. That is, while some researchers engaged in acquiring the advanced graphic and programming technologies of computer science for an actual design system, some[11], instead, began to recognise the needs to reassess the understanding of design alongside computational technologies.

Thus, CAAD research has progressed from computer applications based on logic and algorithms towards a theoretical focus on AI and cognitive science. Moreover, the development of logic programming language and object-oriented language has helped CAAD research to suggest many AI-based applications for design, for example, knowledge-based design systems, expert systems, or case-based reasoning systems. From this, 'AI in design' became one of the important fields in CAAD research.

3.2.2 Artificial Intelligence (AI) in Design

Since the 60s, studies on design intelligence have been around[12], with a broad brief that design is one of the most significant of intelligent behaviours in human[13] and thus the design problems can be solved by intellectual effort. AI in design encompasses computational design, modelling design, modelling design knowledge, modelling the minds of designers, simulating design, automating design and providing tools for designers[14]. Therefore, the field has been studied to a growing extent which has resulted in connecting design with cognitive science, computer science, and cognitive psychology.

Generally speaking, artificial intelligence refers to attempts to develop machines that can reason or behave with human-like intelligence. Patterson (1989) offers the following definition of AI:

> "AI is a branch of computer science concerned with the study and creation of computer systems that exhibit some form of intelligence: systems that learn new concepts and tasks, systems that can reason and draw useful conclusions about the world around us, systems that can understand a natural language or perceive and comprehend a visual scene, and systems that perform other types of feats that require human types of intelligence.[15]"

AI systems are therefore concerned with tasks whose execution appears to involve some intelligence if done by humans; and thus are more successful for tasks based on particular (well-defined) aspects of human knowledge, expertise, and selected reasoning patterns rather than an activities done unconsciously which rely on less well-defined types of knowledge.

Naturally, knowledge plays the important role in building intelligent systems so that AI has emphasised knowing how to go about solving the problem and which knowledge is used – that is, knowledge representation and organisation. This has led to the emergence of knowledge-based systems that depend on a rich base of knowledge in order to perform difficult tasks. These systems were generally designed very differently from conventional programs because the problems usually have no algorithmic solution and rely on inferences to achieve a reasonable solution.

The first attempt in relation to architectural design began with the implication of what makes the difference between novice and successful architect. The rationale is, if experienced designer's knowledge can be formalised and store into the system's knowledge-base, the novice can produce a better solution through using this knowledge or expertise.

The knowledge-base contains the facts and rules that can be applied to automated reasoning procedures; to the facts of a specific design situation. Facts can be expressed as predicates, and rules can be expressed as implications - *if* and *then*. New facts can then be derived automatically from old facts by applying rule systems applied to the given facts. This idea developed into rule-based expert systems and knowledge-based architectural design systems.

Further, the new knowledge representational languages and the advanced strategies of AI have accommodated symbol-processing models for creating better tools for designers, which could not be solved by conventional programs. Flemming (1994) asserts two major reasons of why designers and CAD researchers become interested in AI: (1) commercial CAD systems appeared simply too dumb to be of use in the most interesting phases of design; (2) AI researchers tackle ill-understood problems not susceptible to the structured approach like architectural design. He said:

> "AI was intended to make use of precisely the non-algorithmic, 'heuristic' knowledge that plays such an important role in a designer's daily activities. AI had developed schemes to represent this type of knowledge and general inference mechanisms to reason with it, and this offered possibilities that called for a closer exploration."[16]

Such design systems store the designer's expertise, knowledge, and operating patterns, mainly in the form of rules of thumb. Thus, instead of creating solutions from scratch for every problem situations, they make use of previously stored information in a way that it facilitates their coping with the current problem; for example, heuristic, mutation and analogical reasoning. These approaches are sometimes distinguished from *rigid* expert systems and hence I will explain them separately as expert systems, knowledge-based systems and case-based systems.

Expert systems

Expert systems (or knowledge -based expert system) are historically the most popular branch of AI. They make extensive use of specialised knowledge to solve problems at the level of a human expert. The core technologies were developed during the 1970s', one of the most famous early examples being MYCIN[i]. Such early expert systems were characterised as expert-level advisers or consultants. Today, with different interactive roles, many successful applications can be observed in the business, medicine, science, law, and engineering domains.

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[i] MYCIN was one of the earliest expert systems. It was developed at Stanford University in the mid-1970s to demonstrate that a system could successfully perform diagnoses of patients having infectious blood diseases. (J.Giarratono and G.Riley, pp. 533-536)

The basic components of an expert system included the knowledge base, the user interface, and the inference engine. The inference engine is the basic element that differentiates an expert system from an ordinary computer program. It makes an inference by deciding which rules are satisfied by facts, priorities the satisfied rules, and executes the rule with the highest priority - it mimics a cognitive processor for human-problem solving[17]. That is, the route followed by an expert system is not decided in advance but is constructed dynamically by the inference engine as it applies the rules, in contrast to the classical program where the sequence of decisions is largely programmed explicitly.

Accordingly, the success of expert systems depends on the development of simple rules that can pare down the search tree and make searching efficient, by codifying and placing heuristics used in real-world experts in the inference engine. Nevertheless, they have been built with only specific ranges of tasks and can reason in very narrow fields.

Even in the most successful domain, it is inevitable that expert systems have less breath and flexibility than human experts do[18]. Bonnet *et al.* (1988) state some limitations of present-day expert systems as follows: the absence of any learning capability; the limited methods for knowledge representation; and the rigid reasoning methods[19]. As a result, the applications in the design domain have generally been limited to checking design against legislative requirements, offering planning application guidance, or choosing building/site elements suitable for certain conditions[20].

Knowledge-Based Design Systems

The knowledge base is the model of human knowledge, in which knowledge is represented in an explicit form and knowledge is used to reason for solving a problem. Stefik (1994) distinguishes knowledge in knowledge-based systems from expertise in expert systems as follows.

> While expertise is considered knowledge that is specialised and known only to a few, knowledge is generally founded in books, periodicals and other widely available resources. Thus, expert systems focus on the former specific, expert knowledge in solving problems, but knowledge-based systems do not necessarily

> contain human expertise; it is a computer system that represents and uses knowledge to carry out a task[21].

In contrast to the expert systems, knowledge systems cover all ranges of domains where knowledge is used and created in problem-solving, including general knowledge. Accordingly, as the applications of AI technology have broadened, the design domain also became concerned with knowledge systems.

Mitchell (1994) describes the emergence (during 1980s) of knowledge-based design systems as following:

> "Good designers are not only clever problem-solvers but also turn out to be extremely knowledgeable in the performance of design tasks. This idea was to develop suitable formalisms for expression of design knowledge, to use these to produce knowledge bases that captured what successful designers know (that is, their professional expertise), then to solve design problems by applying automated reasoning procedures to the facts of specific design situation combined with the facts and rules contained in these knowledge bases.[22]"

Thus, AI research in design has tried to discover the appropriate methods for architectural design in representing knowledge, organising memory, and manipulating knowledge. One obvious way has been directed toward using AI technologies, towards the so-called 'rule-based' systems. These systems may succeed in some narrow area of design expertise and some evaluative tasks, but they have suffered from limitations of "rigidity" and "brittleness" articulated as general criticisms of the 'if and then' approach to problem solving[23].

Schmitt (1987) also criticises the practical applicability of rule-base systems in architecture, believing that they are limited mainly due to three reasons: (1) the lack of effective methods for architectural knowledge acquisition and representation, (2) the lack of a widely accepted design methodology, (3) hardware and software technology related restrictions[24].

Another approach derives from following observation: much of the specialised expertise of architects and design engineers (among others) consists of knowledge of how to put physical things together to achieve useful results. This sort of knowledge can be captured by writing *shape grammar* rules specifying that *if* a certain geometric and physical configuration exists *then* you can produce something useful by transforming it in a certain way.

That is, while the left-hand sides of shape rules specify the shape types of interest, and available recognition mechanisms provide a way to find instances of these, the right-hand sides establish potential directions for further development of the design, and the available operators provide the means to carry out that development[25].

The shape grammars may be produced from induction over set of examples taken from existing designs and they are employed as a representational formalism for modelling design transformation, such as Durand's rules and the grammar of Pallidian Villa Plans[26], or the Queen Anne grammar[27]. However, these grammatical approaches have so far received little attention[28] in terms of application within a CAAD environment.

As seen in expert systems, the 'strong knowledge-based' programs (for instance, rule-based, logic and design grammar) typically have fundamental limitations. This is because even though these system can acquire some degree of design knowledge explicitly, they have, in general, no guarantee that a knowledge base is complete and accurate; any knowledge base that is constructed in finite time and stored and processed on a finite machine can only embody a more-or-less incomplete and imperfect sample of the indefinite amount of potentially relevant design knowledge.

For these reasons, Richens (1992) asserts that most of the knowledge-based design programs can address only routine design in narrow domains; they cannot be adapted to the kind of creation that is very crucial in design domain, even in the near future[29]. In spite of such criticisms, some CAAD researchers have still kept challenging the above limitations by applying the increasingly sophisticated, advanced technologies of computer science and AI, and this will be discussed in the next section.

New Approaches in Knowledge-Based Systems

Design processes have unique aspects that are distinguished from other types of problem solving, and hence computers have so far only captured routine or repetitive design and do not support the typical complex design process in a fundamental way[30]. This awareness has posited an agenda for the current CAAD research to gain a clearer insight into the requirements of design. Accordingly, creativity, that is one of the most significant elements in design activity, has become a topic in computational communities - in cognitive science, AI as well as CAAD.

Rosenman and Gero (1993) identify three different types of design in terms of computer operation: routine design, innovative design, and creative design: According to their classification:

> (1) Routine design is accepted as being that the design variables and their ranges are known and the problem is one of variable values; (2) Innovative design is defined as being that design in which the space of known solutions is extended by making variations or adaptations to existing designs; and (3) creative design, in which the state space of possible solutions is extended or a new state space created.[31]

In this way, AI in design usually considers creative design as cognitive process, which is not much different in nature from everyday thinking and reasoning. Thus, creativity is simply interpreted as an introduction of new variables into the design process, which were not originally considered by the designer or design system[32].

Such standpoints derive from the premise that the creative designs can be developed with refinement and adaptation of previous design solutions. In this context, the role of a knowledge base is to provide the appropriate design knowledge and the reasoning mechanism that the designer can use to generate a creative product through analogy, mutation, and association from a rich memory repository. Beyond the successful working systems, these approaches have suggested many significant strategies for non-routine design, for examples, the generation of analogies[33], prototype modification[34], or the mutations of existing designs[35].

Among these models, the concept of *design prototype* was the most attractive as a way of representing and organising design domain knowledge or experience in design systems. This idea was introduced by Gero (1990), and entails a conceptual schema for representing a class of generalised heterogeneous grouping of design elements, interpreted in terms of the three variable groups of *function*, *structure*, and *behaviour*[36]. Thus, design using prototypes is a process in which suitable prototypes are sought, based on the given design specifications, and are instantiated to produce instances that satisfy design goals and constraints.

The evocation of a prototype from memory provides the designer with two types of information: it tells the designer what is possible within a given set of constraints, that is, that an artefact or class of artefacts with a given set of attributes is *feasible*; and more importantly, it contains information about the structure of the space of possible designs—a way of looking at the current problem that proved successful in dealing with similar problems in the past. Thus, the evocation of the prototype makes a set of strategies, relationships, problem decompositions, standard or generic solutions, and default values available for use in achieving the current goal.[37]

The prototype concept that the design process became extended from a routine structural design to creative design by many followers. In creative design, new prototypes can be produced in a number of ways including combination, analogy, mutation, and design from first principle[38]. For example, Maher and Zhao (1993) suggest a system for generating design specifications dynamically using design prototypes as a resource to an initial knowledge-based creative design environment. They classify operations on prototypes into three groups: prototype refinement, prototype adaptation, and prototype creation.[39]

However, Logan and Smithers (1993) criticise such prototype-based approaches in that there is no computational interpretation of these processes and the model itself contains no explicit meta-level or control strategy—deciding which prototype to modify and determining how it is to be modified[40]. That is, though design prototype schema may be accepted as a significant vehicle for representing design knowledge, such system models seem to have inherent problems that limit designer's creativity by constraining them to designs that can be constructed as combinations of prototypes provided by the system's knowledge base.

More fundamentally, it is impossible to generalise designing and design knowledge in terms of certain variable groups, such as 'function, structure, and behaviour[41]'. In the design process, amounts of elements and components are tangled and the relationships between properties are poorly articulated. Thus, at the more abstract and general level the architectural design knowledge is structured, the more easily the combinatorial explosion happens; because of the various functions, behaviours, and a number of different design situations that can exist. One of alternatives to such cognitive models is the case-based approach involving more specific and context-depended knowledge.

Case-Based Systems in Design Domain

Simply speaking, a case-based system is a particular type of knowledge-based systems, which organises knowledge or experiences as cases. Instead of general knowledge, it mainly stores the past experiences of human specialists in a case library for later retrieval. When the user encounters a new problem, it searches for similar parameters within new cases, finds the closest fit and applies the solutions of the old case to the new case. Thus, a case-based problem-solver consists of mainly two processes: indexing to find a suitable precedent, and adaptation to use it in the new problem context.

Kolodner (1993), in *Case-Based Reasoning*, claims that case-based systems are appropriate for 'weak-theory domains' like the design domain, whose phenomena we do not yet understand well enough to record causality unambiguously, and so traditional composition-based (rule-based) methods or model-based reasoning would not have worked[42]. That is why case-based reasoning emphasises the use of concrete instances and manipulation of cases rather than the problem decomposition and re-composition by abstract operators. That is, the instances can provide, more directly, guidance in solving a new problem than can abstracted knowledge.

Thus, case-based reasoning (CBR) is applicable to a wide range of real world situations. In particular, Riesbeck and Schank (1989) state that CBR is one highly promising approach for a new paradigm in knowledge-based systems for design, which can accommodate the cognitive complexity of design problem-solving[43]. While case-based systems have not so far received wide attention in the design context, some AI researcher, such as Kolodner, Goel, and Domeshek, have been focusing on case-based design systems. Below some particular CBR systems related to the design domain are commented upon:

> **CYCLOPS** (Navinchandra 1988, 1991) was the first application of CBR to design. It combines constraint-based solution generation with case-based debugging and repair for design of landscapes. Navinchandra (1991) used a case-based approach to architectural design in which new design ideas are generated by exploring the memory for appropriate cases. By this, new design ideas are generated by composing sub-case from multiple cases.[44]

> **ARCHIE** (Domeshek and Kolodner, 1991; 1992) is a case based design aid (CBDA) for architectural design. ARCHIE contains a case base of designs including both good and bad exemplars annotated with stories that describe key design features and how they function in the building. ARCHIE's initial case library contains ten cases of courthouses and libraries. Each case

comprises over twenty-five stories covering a range of different design concerns. Each case is constructed from drawings, photographs and text obtained from the architect, from visits to the building, and from post-occupancy evaluations (POE's).[45] **ARCHIE-2** currently exists as a set of twenty analysed stories and their accompanying guidelines, a preliminary vocabulary for describing those stories, and an interface prototype developed in Supercard™ on an Apple Macintosh™[46].

DEJAVU (Bardasz and Zeid 1991, 1992) is a domain-independent design assistant. It acquires design process models from a designer as new problems are solved. Over time, as the system becomes knowledgeable in the domain of deployment, it acts as a design assistant, retrieving past design cases suitable for reuse in response to a user-specified problem specification.[47]

CADSYN's (Zhang and Maher 1991) domain is structural design of buildings. It integrates case-based reasoning with problem decomposition and constraint processes. Solutions are derived by finding the most relevant previous design situation and transforming the potential solution to fit the new design situation using a domain specific constraint satisfaction approach.[48]

AskJef (Barber et al. 1992) is designed to help software engineers in designing human-machine interfaces. The different types of knowledge—design cases, design stories, design objects, and prototypical design error—are cross-indexed to enable the designer to navigate through the system's memory to gain an understanding of the range of interface design problems.[49]

Fischer's group (Fischer, Lemke, McCall, and Morch 1991; Fischer and Nakakoji 1993) has built a series of design environments, such as the **JANUS** system for architecture, that integrate a range of support for design tasks. Integration of argumentation, design information, and access to stored cases in the designer's working environment (a structured "construction kit" editor) is prominent in the work of them.[50]

ArchieTutor (Goel et al. 1993) is to support design teaching by helping beginning architectural students in understanding the nature of the design domain of office buildings, and the structure of design problems and solution. It is an experiment in combining case-based and multimedia technologies.[51]

PRECEDENTS (Oxman and Oxman 1993) is a library of significant precedents which provide relevant ideas for current design. The library is intended to support initial stages of architectural design through structured knowledge from past experience. The sub-domain is the design of urban art museums. The system is developed in a prototype Hypermedia system for experimentation and demonstration.[52]

SEED (Flemming, Coyne and Woodbury 1993), a software environment to support the early phases in building design intends to provide systematic and broad support for both the creation and evaluation of new design and their reuse in a new, but similar context; and to support the preliminary design of buildings in all aspects that can gain from computer support. SEED supports work in each design phase by a specific module, which offers designers a broad range of form generation capabilities and each module has a problem specification component, generation component, and evaluation component.[53]

As seen above, the case-based systems for design have been developing: some researchers have concentrated on automated reasoning systems, and thus they have focused more on sophisticated case-retrieval, adaptation, even learning technologies. Others, mainly in the architectural design field, have attempted to produce interactive systems or case-based design-support systems, and thus they have focused on case organisation, mapping between target and source, or analogical reasoning[54].

For example, the JULIA[ii] system can be automated to some degree, such as in problem decomposition, retrieval and adaptation of cases as well as indexing and storage of cases. However, the problems in the architectural design domain do not have a clear specification and hence they are rarely backed up by data on human reasoning; this is why design domains have focused on the human-computer interactive case-based system rather than reasoning systems.

[ii] JULIA (Hinrichs 1988, 1989, 1992) is a case-based reasoning system in the domain of meal planning. *see*, Hinrichs, T. R., *Problem Solving in Open Worlds: A Case Study in Design*, Erlbaum Associates, Hillsdale, New Jersey, 1992.

3.3 The Two Trends in the developments of CAAD

I have reviewed the applications of computers in the architectural design domain, ranging from commercial drafting software to the academic research of AI in design. From this study, I identify two obviously different ontologies of computers for architectural design, and the shifts in the CAAD research focus over the past 40 years, as follows.

3.3.1 Two Different Directions in CAAD

Since CAD was introduced in design studies, many design activities have been computed, such as problem analyses, drafting, visual representations or even certain solution generating algorithms. There are two obvious tendencies observed in CAAD research: (1) viewing computers as a thinking machine and (2) viewing computers as a design tools. While the first direction has tried to solve design problems by representing design knowledge, rules or principles in computers, the second direction has aimed to help designer to draw faster, or produce photo-realistic renderings and animation in real time. The characteristics of two directions are distinguished in the following table.

Table 3.1: *Two different directions in CAAD: Computer as an Intelligent system and computer as a Design tool*

	Intelligent System	Design Tool
Computer	As a thinking machine	As a design tool
Concept	Computability of design	Usability of computer
Ideology	Rationalism	Pragmatism
Related fields	Artificial Intelligence	Computer Science
Feature	Academic, Theoretical	Commercial, Practical
Design Systems	Knowledge-based systems, Expert systems, Case-based systems	CAD drafting or modelling programs, Information-management systems

As seen above, the first category – the computer as an intelligent system - regards computer as a thinking machine that has some structured knowledge to solve design problems and thus its theoretical framework is borrowed from information-theories, in which design is interpreted as a problem-solving, a decision-making or a knowledge-depended activity. It emphasises design knowledge, information and the designer's cognitive process, so that its characteristic is academic, experimental and future-oriented. As discussed in the previous section, despite of the development of technologies in computing and AI, this field has not developed for the design discipline as much as had been anticipated.

The second category has focused on design supporting tools such as drafting, modelling or representing environments. Their aims, whether to be commercial or not, lie in improving the usability of computer for design and the efficiency of design; that is, in developing a friendly, usable application by employing state-of-the-art techniques of computer science. In addition, the developments in design presentation technologies now led by the commercial CAD companies, such as three-dimensional modelling, simulation or virtual reality, will inevitably be continued.

3.3.2 Changes in the CAAD Research Focus

Since design methodologists started dealing with the computation of design in 1960s. Researchers from both sides – computer as intelligent system and computer as design tool - have evolved their technologies and theories for CAAD. It can be observed that the main stream of CAAD research has shifted back and forth between above two directions over the past 40 years. Here, I identify four periods broadly by decade. Of course, this observation does not indicate the developments of computing generally, but is limited to the shifts between the two different views of CAAD research.

- **First period** (the 1960s): The architectural system of the 1960s introduced as a means to facilitate the existing established design methods, with the goal of automated design systems. Thus, the role as drafting or visualising tool was not paid much attention due to the capability of software and hardware.
- **Second period** (the 1970s): By the 1970s, a number of ambitious software design projects were commissioned by the public sector and useful work for architectural design started - including planning, evaluation of alternatives, cost planning or structural design. This was also the era when the naiveté of the approaches to

automation become obvious[55]. At the same time, simple drafting systems became developed and were taken a growing interest in by CAAD research.

- **Third period** (the 1980s): During the 1980s, the hardware improvements and the notable development of commercial CAD applications led PC-based architectural offices to become widespread. As the computer as drafting systems succeeded, in turn, the academic interest dwindled[56] and interest moved towards more philosophical problems.

  Along with the awareness that logic and algorithms alone could not solve the related design problems, CAD researchers started to draw new clues from advanced technique in AI. In this period when some expert systems were successfully implemented in specific fields, many intelligent design systems were suggested and experimented with by enthusiastic academic researchers.

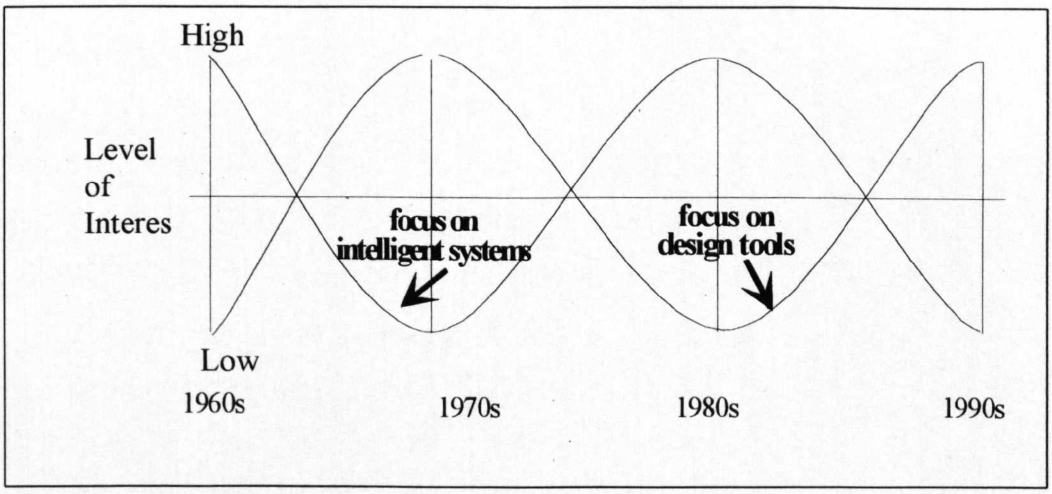

Figure 3.1: Shifts in the CAAD research focus over the past 40 years

- **The forth period** (the 1990s): CAD software industry continue to flourish during the 1990s, and thus many notable drawing and representing tools appeared in increasingly sophisticated form and at shorter intervals. Meanwhile, compared to the remarkable commercial success of graphic design applications, intelligent design systems have proven to be a much more difficult and elusive undertaking than anticipated[57]. In addition, the disappointment in the result of 'The Fifth Generation Computer Systems (FGCS)' project[58] led to a decline in interest in the brief on the feasibility of AI in design.

In sum, the view of computer as a design tool has been given varying degrees of attention by researchers, but the applications have been continuously improved in form of advanced graphic technologies. Along with the commercial success of CAD software, the steady increase in power and the reduction in cost of computer hardware have made commercial CAD systems more popular in design practice and this in turn has had a significant effect on architectural design practice.

Meanwhile, despite the development of AI technique and computer languages, intelligent systems for the design domains, especially for architectural design, have evolved very little, compared to the other fields and the expectation of the earlier CAD researchers. Even though, using the relatively new technology in AI such as neural networks, case-based reasoning and fuzzy reasoning, most of them fail to generate reasoning systems up to a significant level to offer a plausible solution to real design problems.

Gero (1987) predicted, in a paper presented in CAAD Future '87, that intelligent systems would be the core tools in computer-aided design with their ability to automate reasoning through automating inference processes[59]. However, after 10 years, he (1997) acknowledges the difficulty of applying computer reasoning in the design domain, and that there are still very few well-developed intelligent design support systems in use today[iii]. The decrease in the number of papers on the subject in CAAD conferences demonstrates the recent change of the concern of CAAD research. That is, it is a conspicuous phenomenon in CAAD research to shift their interests from the automating or reasoning of design to the more sophisticated design tools by applying the state-of-the-art computer technology to the design domain.

3.4 Conclusion: New Approaches to CAAD

In conclusion, there is so far no design system that can give complete support to all architectural design activities. That is, although some small parts of the design

[iii] This observation came in an address to in the 7th international conference on CAAD Futures 1997 held in Munich, Germany, 1997.

processes are implemented on computers, the system for a real design remains still being developed in both CAD software companies and the academic research.

The difficulties in building a design computational environment result from the combination of many obstacles: the lack of technology; the limitations of computability of design; the incompatible nature between designing and the computer, and so on. In order to overcome these obstacles, CAAD researchers have continued to suggest approaches to new design computational environments by responding to the capabilities of current computational technologies, or more philosophically, by proposing theories of evolution.

Man-Machine Symbiosis Environment

As an alternative to the failure of automated design as a whole, this approach – man-machine symbiosis computational environment - delimits proper roles for the human designer and the machine. That is, it combines human and computer capabilities for design in a complementary, integrated manner. Some notable examples include the *partnership paradigm*[60], *computational design support environments*[61], *Knowledge-Based Design Support System*[62].

Mitchell (1994) suggests a more practical approach: "to divide up the labour of designing in such a way that the human designer gets the ill-defined hard parts but the machine reduces the grunt work by dealing automatically and efficiently with well-defined easy parts[63]". This may be a realistic statement in complementing the limitations of the existent CAD environments. Furthermore, it becomes a feasible assumption that computational systems can play the most effective role in enhancing creativity within human-machine design systems where the division of labour between the two participants supports exploration of problem formulations and solution spaces[64].

Though the symbiosis between man and machine appears to be possible theoretically, it is by no means easy to define which functions are allocated to human or machines on the basis of man-machine capabilities. That is, as Coyne and Subrahmanian (1993) pointed out, because we understand little of the design process and we lack a comprehensive model for integrating the abilities of man and machine into a complete design process[65]. Based on these reasons, some research has focused more on the design of the user interface that can provide architects with the friendly and suitable design environment rather than the design of functional allocation in man-computer system.

Integrated Systems

Most applications for design have been developed from a particular theoretical, technical background with different functionalities; and hence each plays a partial role in the design process. Such single-purpose applications can not meet all of the designer's demands. Accordingly, the demands of the integrated system reaches right back to the start of CAD in the 1960, with an assumption that computers would be used to store and operate on information for all design processes[66]. However, such ambitious systems that integrate all phases of the design life-cycle still remain unrealised.

Recently, the development of AI in design has led to the embedding of AI-based applications into traditional programming; that is, combining CAD programs with relatively new technologies from logic programming and knowledge-based systems of AI. For these systems, design objects have a specific behaviour as well as its own property, for example a column knows that it must locate itself between beams or slabs and so on[67]. Each piece of intelligent behaviour can be formalised as a rule that is employed in creating and displaying objects and geometry. In addition, such systems also offer design advice and standards across the domain disciplines[68].

However, these attempts to apply CAD program to the real design problem have been restricted to sub-problems that can be quantified, such as staircase construction, welding, lighting, and thermal analysis[69]. The basic difficulties in integrating reasoning systems with CAD programs lie in the incongruous functionalities between them. That is, each application is designed for a completely different environment and each has completely different functionality or reasoning system - the logical or symbolic reasoning and the geometric reasoning needed to create or to analyse geometric models[70].

A Design Medium for Communication and Collaboration

Recognising the difficulties of developing the generic design tools, CAAD researchers have attempted to gain new ideas from the state-the-art computational technologies or the advanced commercial software. One of the most significant

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design domain, and then will suggest a new design model – a *design thinking/action phenomenon*.

Reference

[1] Harfmann, A., 'The rationalising of design', in *Computability of Design*, Y. Kalay (ed.), John Wiley & Sons, New York, p. 6, 1987.

[2] Richens, P., 'The next ten years', in *Computers in architecture tools for design,* François Penz (ed.), Longman, Essex, p. 143, 1992.

[3] Mitchell, W.J., *Computer-Aided Architectural Design,* Petrocelli/Charter, New York, 1977

[4] Schmitt, G. N., and W. Oechsline, 'Computer aided architectural design futures, in *CAAD futures '91,* G.N. Schmitt (ed.), Vieweg, Wiesbaden, p. 9, 1992.

[5] Schmitt, G, 'Design medium – design object', in *Proceedings of the 7th International Conference on Computer-Aided Architectural Design Futures*, R. Junge(ed.), pp.3-15, 1997.

[6] Pohl, J. and L. Myers, 'A distributed co-operative model for architectural design', in *Knowledge-Based Computer-aised Architectural Design,* G.Carrara and Y.Kalay (eds.), p. 215, 1994.

[7] Laudon, K. and J. Laudon, *Essentials of Management Information Systems: Organisation and Technology*, Prentice-Hall International, Inc., NJ, pp. 147-211, 1995.

[8] Winograd, T, and F. Flores, *Understanding Computers and Cognition,* Addition-Wesley Publishing Company, Inc., Reading, p. 152, 1987.

[9] Crosley, M.L., *The Architect's Guide to Computer-Aided Design*, John Wiley & Sons, New York, pp.4-12, 1988.

[10] Mitchell, W.J., *Computer-Aided Architectural Design,* Petrocelli/Charter, New York, p. 58, 1977.

[11] For example, Bijl, A., *Computer Discipline and Design Practice: Shaping Our Future*, Edinburgh University Press, Edinburgh, 1989.

[12] Oksala, T., 'Design intelligence: Evolutionary and cognitive aspects', *Automation in Construction* 3, p. 105, 1994.

[13] Oxman, R., 'Cognition and design', *Design Studies*, Vol. 17, No.4, pp. 337-340, 1996.

[14] Coyne, R. and A. Snodgrass, 'Rescuing CAD from rationalism', *Design Studies,* Vol. 14, No. 2, p. 101, 1993.

[15] Patterson, D.W., *Introduction to Artificial Intelligence and Expert Systems*, Prentice-Hall International, Inc., p. 2, 1989.

[16] Flemming, U., 'Artificial intelligence and design: a mid-term review', in *Knowledge-Based Computer-Aided Architectural design*, G. Carrara and Y. E. Kalay (eds.), Elsevier, Amsterdam, pp.1-4, 1994.

[17] Giarratano, J. and G. Riley, *Expert Systems: Principles and Programming*, PWS-KENT Publishing Company, Boston, pp 107-183, 1989.

[18] Stefik, M., *Introduction to Knowledge Systems*, Morgan Kaufmann Publishers, Inc., San Francisco, p. 296, 1994.

[19] Bonnet, A., J.P. Halton and J.M. Truong, *Expert Systems*, translated by J.Howlett, Presntice Hall, New York, pp. 47-49, 1988.

[20] Lawson, B., *How the Designers Think* (2nd ed.), Butterworth Architecture, Oxford, p.202, 1990.

[21] Stefik, M., *Introduction to Knowledge Systems*, *op. cit*., pp. 299-310.

[22] Mitchell, W.J., 'Three Paradigms for Computer-Aided Design', in *Knowledge-Based Computer-Aided Architectural Design*, G. Carrara and Y.E. Kalay (ed.), Elsevier, pp. 379-388, 1994.

[23] Coyne, R.F. and E. Subrahmanian, 'Computer supported creative design: a pragmatic approach', in *Modelling Creativity and Knowledge-Based Creative Design*, J.S. Gero and M.L. Maher (eds.), Lawrence Eribaum Associates, pp. 295-304, 1993.

[24] Schmitt, G. 'Expert systems and interactive fractal generators in design and evaluation', in *CAAD futures '87*, Elsevier, pp. 91-106, 1987.

[25] Mitchell, W.J., *The Logic of Architecture*, MIT Press, Cambridge, p. 181, 1990.

[26] *see*, ibid., pp. 149-179.

[27] *see*, Flemming, U., 'More than the sum of the parts: the grammar of Queen Anne', *Planning and Design*, Vol. 14, No. 3, pp. 323- 350, 1986.

[28] Oxman, R.E. and R.M. Oxman, 'Refinement and adaptation in design cognition', *Design Studies*, Vol.13, No.2, p.121, 1992.

[29] Richens P., 'The next ten years', in *Computers in Architecture Tools for Design*, F. Penz(ed.), Longman, Essex, p.143, 1992.

[30] Coyne, R.F. and E. Subrahmanian, 'Computer supported creative design: a pragmatic approach', *op. cit*., pp. 295- 296.

[31] Rosenman M.A. and J.S. Gero, 'Creativity in design using a design prototype approach', in *Modelling Creativity and Knowledge-Based Creative Design*, *op. cit*., pp. 111-115.

[32] Gero, J., 'Design prototypes: A knowledge representation schema for design, *AI Magazine 11 (4)*, pp. 26- 36, 1990. And Gero, J.S. and M.L. Maher, *Modelling Creativity and Knowledge-Based Creative Design*, Erbaum, Hillsdale, NJ, 1993.

[33] Maher, M.L., F. Zhao, and J.S. Gero, 'A knowledge-based model for creative design, in *Proceedings of NSF Engineering Design Research Conference*, University of Massachusetts, pp. 333-346, 1989.

[34] Gero, J., 'Design prototypes: A knowledge representation schema for design, *op.cit.*, pp. 26- 36.

[35] Murthy, S.S. and S. Addanki, 'PROMPT: An innovative design tool', in *Proceedings of AAAI Sixth National Conference on Artificial Intelligence*, Seattle, pp. 637- 642, 1987.

[36] Gero, J.S., 'Design prototypes: a knowledge representation schema for design', *Magazine 11 (4)*, *op. cit*., pp. 30- 31.

[37] Logan, B. and T. Smithers, 'Creativity and Design as Exploration', in *Modelling Creativity and Knowledge-Based Creative Design*, *op. cit*., pp. 139-175.

[38] Rosenman, M.A. and J.S. Gero 'Creativity in design using a design prototype approach', in *Modelling Creativity and Knowledge-Based Creative Design*, *op. cit*., pp 111- 138.

[39] Maher, M.L., and F. Zhao, 'Dynamic associations for creative design', in *Modelling Creative and Knowledge-Based Creative Design*, *op. cit*., pp.329- 351.

[40] Logan B. and T. Smithers, 'Creativity and design as exploration', in *Modelling Creativity and Knowledge-Based Creative Design, op. cit.*, pp. 139-175.

[41] Gero. J. S., 'Design prototypes: A knowledge representation schema for design', *AI Magazine, op. cit.*, p. 31.

[42] Kolodner, J., *Case-Based Reasoning*, Morgan Kaufmann, pp. 14-16, 1993.

[43] Riesbeck C. and R.C. Schank, *Inside Case-Based Reasoning,* Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1989, quoted by R. Oxman and R. Oxman, 'Precedents: Memory structure in design case libraries', in *Proceedings of CAAD Futures '93*, U.Flemming and S. Van Wyk (eds.), Elsevier, pp. 273-287, 1993.

[44] Bhatta S., A. Goel and S. Prabhakar, 'Innovation in analogical design: a model-based approach', in *Artificial Intelligence in Design '94,* J. Gero and F.Sudweeks (eds.), Kluwer Academic Press, Dordrecht, the Netherlands, p. 72, 1994.

[45] Gross M., C. Zimring and E. Do, 'Using diagrams to access a case base of architectural designs', in *Artificial Intelligence in Design '94, op. cit.*, pp.129-144.

[46] Domeshek, E. and J. Kolodner, 'Case-based design aid for architecture', in *Artificial Intelligence in Design '92,* J.S.Gero (ed.), Kluwer Academic Publishers, Dordrecht, pp. 497- 515, 1992.

[47] Kolodner, J., *Case-Based Reasoning, op. cit.*, p. 621.

[48] Ibid., p. 593.

[49] Goel, A. et al., 'A Cross-Domain Experiment in Case-Based Design support: ArchieTutor', in *Case-Based Reasoning: Papers from the 1993 Workshop,* AAAI Press, California, pp. 112- 113, 1993.

[50] Gross M., C. Zimring and E. Do, 'Using diagrams to access a case base of architectural designs', in *Artificial Intelligence in Design '94, op. cit.*, pp.129-144.

[51] Goel, A. *et al.*, 'A Cross-Domain Experiment in Case-Based Design support: ArchieTutor', *op. cit.*, pp.112- 113.

[52] Oxman, R. and R.M. Oxman, 'PRECEDENTS: Memory structure in design case libraries', *op. cit.*, pp. 273- 287.

[53] Flemming, U., R.F. Coyne, and R. Woodbury, 'SEED: A software environment to support the early phases in building design', in *ARECDAO 93: Proceeding International Conference on Computer Aided Design in Architecture and Civil Engineering,* Barcelona, Spain, pp. 111-122, 1993.

[54] Visser, W., 'Two functions of analogical reasoning in design: a cognitive psychology approach', *Design Studies,* Vol. 17, No.4, pp. 417-434, 1996.

[55] Richens, P., 'The next ten years', in *Computers in Architecture Tools for Design,* F. Penz (ed.), Longman, Essex, p.143, 1992.

[56] Richens, P., 'Does knowledge really help? CAD research at the Martin Centre', *Automation in Construction,* No. 3, p. 219, 1994.

[57] Pohl, J. and L. Myers, 'A distributed co-operative model for architectural design', *op. cit.*, p. 205.

[58] Ueda, K., 'The Fifth Generation Project', *Communication of the ACM,* Vol. 36, No. 3, pp. 48-76, 1993.

[59] Gero, J. and M. Maher, 'Future roles of knowledge-based systems in the design process', in *CAAD Futures '87,* T. Maver and H. Wagter (eds.), Elsevier, 1987.

[60] *see*, Swerdloff L. M. and Y. E. Kalay, 'A partnership approach to computer-aided design',in *Computability of Design*, Y. E. Kalay (ed.), John Wiley & Sons, New York, 1987.

[61] *see*, Coyne, R.F. and E. Subrahmanian, 'Computer supported creative design: A pragmatic approach, *op. cit.*, pp. 295- 304.

[62] *see*, Oxman, R. and R. Oxman, , 'Case-based design : Cognitive models for case libraries', *op. cit.*, pp. 45-68.

[63] Mitchell, W.J., 'Three paradigms for computer-aided design', in *Knowledge-Based Computer-Aided Architectural Design*, *op. cit.*, p. 381.

[64] Carrara G., Y.E. Kalay and G. Novembri, 'Knowledge-based computational support for architectural design', in *ACADIA 1994*, pp 5-6, 1994.

[65] Coyne, R.F. and E. Subrahmanian, *op. cit.*, pp. 295- 304.

[66] Bijl, A., *Computer Discipline and Design Practice: Shaping Our Future*, Edinburgh University Press, Edinburgh, p. 82, 1989.

[67] Richens, P., 'The next ten years', *op. cit.*, p.161.

[68] Reinschmidt, K. and G. A. Finn, 'Smarter computer-aided design', *IEEE Expert*, Vol. 9, No. 4, pp. 50-55, 1994.

[69] Pohl, J. and L. Myers, 'A distributed co-operative model for architectural design', *op. cit.*, p. 215.

[70] Ibid;, pp. 205-242.

[71] Bijl, A, 'On knowing—feeling and expression', in *CAAD Futures '91*, G.N. Schmitt (ed.), Vieweg, Wiesbaden, pp. 157- 176, 1992.

[72] Pohl, J. and L. Myers, 'A distributed co-operative model for architectural design', *op. cit.*, p. 205.

[73] Gero, J.S., 'What are we learning from designers and its role in future CAAD tool', in *Proceedings of CAAD Futures '97*, R. Jung (ed.), Kluwer Academic Publishers, Dordrecht, p. 61, 1997.

Chapter

4

An Architectural Design Model: Design *Thinking/Action*

Abstract: *This chapter suggests a phenomenon of design: design thinking/action as a design model. The arguments are based on the assumptions that the designer's perception, thinking and action do not function separately, and thus the activities – doing thinking and design action – occur simultaneously or immediately. Before suggesting this design model, I articulate the limitations of problem-solving paradigm as a typical model for CAAD. At the end of this chapter, I discuss the two salient features of design activity – creative activity and visual thinking.*

CHAPTER 4: AN ARCHITECTURAL DESIGN MODEL: DESIGN *THINKING/ACTION*

The design model is a representation of philosophies or strategies proposed to show how design is (or may be) carried out. Over the years, several design models have been proposed by design studies and CAAD research and they are still being employed in a theoretical establishment for design systems, or hopefully, in performing a design practising task. As discussed in chapter 2, the design models for CAAD have usually been presented within the paradigm of a problem-solving or information-process paradigm, such as a systematic three-step model, a heuristic knowledge model, or more recently, a cognitive model.

By supposing that the design process could be interpreted as a systematic process, a rational decision-making or a knowledge-dependent activity, the early design models attempted to mimic design activities in the computer and finally to concoct an automated design system. To do so, CAAD research has, either willingly or unwillingly, constructed computational explanations of design phenomena by borrowing the theories, tools, and the language of computer science (in particular, AI), and forced the complicated designing process into a rational problem-solving or cognitive paradigm. In the process, designing has been interpreted in the terms unfamiliar as design (and design process) descriptors, like intelligence, language, decision-making, knowledge, or reasoning.

In the same vein, Cross (1991) asserts that the paradigm, viewing design as problem-solving in an information-processing mechanism, has failed to capture the full complexity of design thinking. He claims that the lack of an adequate paradigm has inhibited the transfer of knowledge from research into practice and education[1]. Such recognition has led some researchers to move away from the notion of 'design as a rational problem-solving process'. Schön (1983) has proposed a different paradigm for architectural design, describing design as a process of 'reflection-in-action'[2]. He (Schön, 1985) suggests an alternative epistemology of practice in which the design process is regarded as a reflective conversation with the situation rather than a rational search process; and in which the professional artistry is more emphasised as design knowledge than technical expertise [3]. Such realistic theoretical bases put his new concepts to designing in a good position for possible application in design practice or the design studio for architectural education, even though not directly for the application in computation of design.

At any rate, these foregoing works encourage this study to investigate the limitation of existing paradigms for CAAD and cognitive models, and to seek a new theoretical framework for design systems.

4.1 The Limitations of the Problem-solving paradigm in design

Many CAAD researchers have taken up the theoretical frameworks of 'design as an information processing' or 'design as a problem-solving activity', and have suggested some design systems under this paradigm. In fact, this paradigm has contributed much of the conceptual framework in computerising design models for over thirty years, and it has played an underlying role in programming design activities into design systems. The main reasons for CAAD study to linger in this paradigm might be summarised as follows:

(1) Design researchers gain access easily to the well-established information theories in this paradigm, which provide the theoretical background of computer sytstems without further effort;

(2) This paradigm has provided the useful mechanisms to mimic the performance of human design activity into a computer program[4]; and

(3) The sharing terminology in this paradigm provides a good medium not only for conceptualising design but also for communicating with the neighbour sciences and technology.

Here, designing has been regarded as a special kind of problem-solving process, and the term of the designer is replaced with design agent or design system to emphasise the role of the computer. In addition, designing is defined as a search or explorative process towards a solution, in which the problem space is limited by the information processing capacity of the design agent's knowledge or experience. These are the basic assumptions for the design problem-solving systems.

Nevertheless, to date the computer plays a limited problem-solver's role in designing; at best, they serve as a tool to support the human agent, as a problem simulator for creating solutions or as a design reference by offering design knowledge and insights. This means that the computer is not employed as an intelligent problem-solver, but more as a design tool in design. The awareness results in the suspicions whether this paradigm may be inadequate or inappropriate for building computer systems for design. Thus, the paradigm should possibly be complemented or replaced by a new theoretical framework. In the next section, I will discuss the limits of the present paradigm for design, in the lights of the features of design problem, design process, design system, and design cognition.

4.1.1 The Wickedness of Design Problems

As seen in chapter 2, the problems occurring in design are generally recognised as ill-defined, ill-structured, or wicked problems, and hence most of them are hard to establish problem formulations; to program design generators and test procedures; and then to automate the process. Meanwhile, this paradigm has posited that such ill-structured problems could be dealt by decomposing with well-defined sub-problems. From this, some narrowly specialised design sub-problems have been formulated with reasonably sophisticated solution algorithms, and have been implemented in some successful applications.

However, the problems that the designer deals with at a high level are not amenable to mathematical, analytical techniques in the solution at the drafting phase, but lie in the actual realisation of design thinking. This may be in the realm of the senses, of imagination, and of judgement[5]; or in the realm of primarily cultural and aesthetic matters[6]. In consequence, we should considered an alternative approach to that which believes that design problems consist of well-structured sub-problem, and that a design solution can be resolved through searching in a problem space.

4.1.2 The Limitations in Design Problem-Solving Process

In this paradigm, design is usually defined as a series of information transformations from a design problem into a solution by applying operations. It adapts the view that, during designing, the designer is involved in a heuristic search activity, a goal-directed, or an exploratory process, accompanying a continuum of selection and decision-making. By choosing better solutions among alternatives, information or operator strategies, the problem space becomes reduced and then the solution process moves in a more convergent direction. Thus, if mathematical or logical models can explain design, and if sufficient knowledge that gives rise to certain consequences can be represented in computer, design systems can produce a reasonable solution or can fully automate the design process.

Even though such problem solving models are useful as the framework for computerising a design, this view is somewhat at odds with the viewpoint of conventional designing. That is because designing usually depends rather more on intuitive, subjective judgement and value-laden problem-solving activities than on decision-making and knowledge-dependent activities. Moreover, design cannot be fully described by a reasoning process so that the rational choice in the problem space may be beyond the capability of a designer or design systems. Any decision or judgement, even of well-defined sub-problem in design, will be changed until design finishes and hence it is perhaps stochastic rather than deterministic[7].

That is, when the designer arrives at a point where design extends beyond the designer's cognitive capability, the design decisions cannot help but depend on the designer's subjective judgement that is influenced by personal intentions, brief, values, experience, culture, mood, and so forth. Accordingly, the design process then becomes a value-laden decision-making one with an inner confidence that cannot be justified by reason. This makes it more difficult to examine where a design solution comes from, as well as difficult to develop consequent intelligent CAD systems.

4.1.3 The Limitations of Design Cognitive Models

The basic concept of design cognitive models is built upon a Gestalt view that could be encapsulated as follows:

> "People do not spring into action but engage in thinking before they commit to action; thinking itself is a well-learned procedure for interpreting inputs, retrieving relevant knowledge and selecting appropriate actions from each individual's repertoire of behaviours; and knowledge must be mentally represented in memory.[8]"

From this observation, most cognitive models have clung to design knowledge or memory systems, and hence have focused on knowledge retrieval from a memory and manipulating memory, that is, knowledge representation and organisation.

But, the design process involves not only cognition that is defined as the acquisition and the use of knowledge, but also engages in other mental operations and design action, such as intuition, analogy, visual experience, or its learning. In order to arrive at a solution in a closed-world, knowledge is a necessity; but in order to create a design, knowledge is just one of the tools to enable design thinking and design action. In other words, knowledge alone can not produce a design solution, rather it exists only as a tool for assisting various design cognitive activities.

Accordingly, any cognitive model cannot explain the entire design thinking. That is, parallelled with intellectual efforts, the designer's other conscious mental efforts (e.g., intuitive inspiration, imagery, or imagination) cannot be overlooked in the creative phase in design processes.

4.1.4 The Limitations of Computer as a Problem-Solver

Ideally, intelligent CAD systems should be able to generate or solve a design problem, under the assumption that designing can be predictable and tested in a recurring pattern, and can be manageable with a set of knowledge and operators. However, this system requires a huge numbers of chunks of knowledge and the huge memory capacity to enact design processes.

Moreover, during designing, design knowledge is continually influenced and changed by the external world or past experiences. The designer's repertoire is not a fixed collection of chunks of knowledge but it may be an organism that responds to a specific design task and a particular situation. It becomes difficult or impossible to represent and manage them in a memory system. More recently attention has turned to trying to mimic the human and organic nature of the processes involved by techniques such as neural networks. But works in these related areas are still in its infancy.

As a result, despite the advanced methods and strategies employed in AI, intelligent CAAD systems had limited success. Eastman (1994) states that CAD systems have achieved great utility only in areas where (1) the elements being composed are known; (2) the performance dimensions to be achieved are well defined; (3) and the rules of composition are well understood[9]. Except for some sub-problems in designing, it is understood that most design problems do not involve well-defined elements, functionality and composition rules. Thus, it may be the case that we should not expect AI to provide highly automated design systems for anything but the most routine and well-structured problems that arise during design[10].

4.2 Design as a Phenomenon of Thinking-Action

In the previous section, I argued that designing is an alien mode of problem-solving activity and hence this paradigm has eventually failed in developing design models and computer systems. The 'designerly ways of thinking[11]' are quite different from that of other problem-solving tasks. Consequently, there is a significant necessity to establish a new theoretical model for computerising architectural design. It should adapt designerly ways of understanding what designers actually do and think. This could lead to finding out what is missing in the design problem-solving paradigm; and help to establish a new theoretical background for computing architectural design.

To do so, I intend to posit a simple design process, under the acknowledgement that the more prescribed and systematic design procedure the design model has, the more divergent it is from real design processes. Thus, I divide the process into three phases – the problem mode, the design mode and the detail design mode.

Design starts with recognising a problem in the task: this could be called the problem mode. This recognised problem is immediately transferred into the surface of the design mode. In the design mode, the designer issues design problems; represents ideas and concepts; and develops them into a design. Most of the design process, from the first embryonic ideas to the final details, occurs in this mode and the associated design concepts have influence on the entire design process. It is often called 'the early design stage' or 'the conceptual design stage', yet especially in architectural design, the conceptual design mode actually takes place through the entire design process until the drafting procedure. Accordingly, the design mode cannot be accurately distinguished as the early design stage or conceptual design stage, as stated in chapter 1.

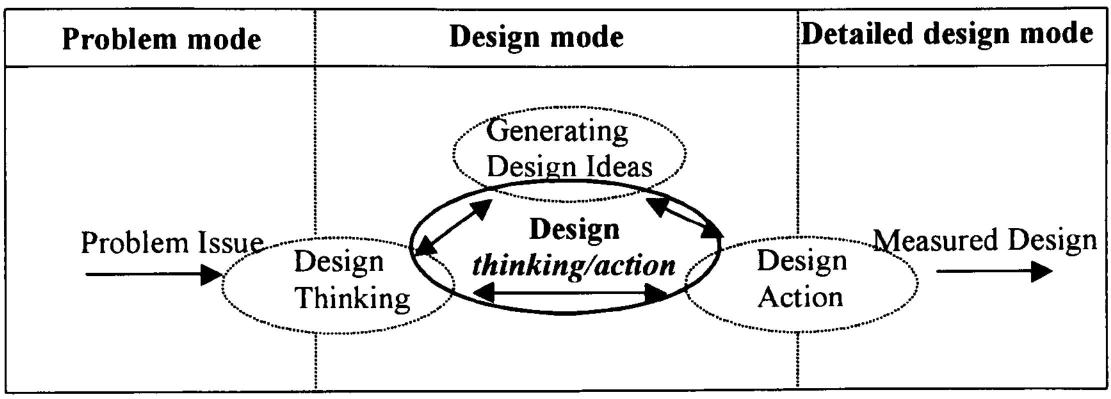

Figure4-1: Three different modes in the design thinking-action process

In the design mode, design activities may involve at least one, or all three activities – generating design ideas, design thinking and design action; their activities have no precise boundaries, and appear to be in a state of muddle in practice (see figure 4-1). That is, generating ideas, design thinking, and design actions occur simultaneously: this will be described in this thesis as a design phenomenon of *thinking-action*.

4.2.1 Design Thinking

Design thinking is regarded as the mental activities involved in forming a design concept or generating an image, in which the designer interprets and perceives a situation based on his knowledge and experience. Design thinking is a cognitive, self-concious process, in that it starts with the recognition of a problem and then involves in a conscious thought process, such as interpretation, understanding, learning or intuition.

Problem Recognition

The design problem comes from the designer's attention to perception and thought process. It emerges at any time and at any stage in the design process Whenever the breakdown occurs in between the designer' intentions, user/client requirements and a design situation, such as site conditions, cost, or climate, the designer recognises a problem to be designed. Thus, problem recognition can be defined as a designer's attention or identification against a given situation.

It may be much easier if the issued problems can be described as being in problem analysis, searching and decision-making stages as seen in a typical problem-solving process. However, a design problem always arises in situation where it exists and its nature depends highly on design context. Moreover, any situation in design is never fixed or predictable because it continuously changes during design, even in the same designer's perception of the same context. Accordingly, before engaging in analytical thinking, most designers direct attention and activity towards design actions by generating design ideas. During the design actions, they come to understand more clearly design problems and to discover new problems.

Understanding a Design Problem

To define the meaning of 'understanding' may be one of a laborious philosopher's tasks. However, in this thesis, 'understanding' is limited as the designer's interpretation (or perception) of a problem in a given situation. As the designer understands a situation or problems in a task, design problems can be developed into a design concept or idea in the designer's mind. In fact, some complex design problems require significant intellectual efforts to establish a design concept.

Best (1969) states that to tackle such design problems, we have to interpret them and this interpretation is always a simplification process. From this respect, he considers designing as a *variety-reducing process*, where the filtering mechanisms reduce the issued problems to the few chunks of information that reach an understanding status[12]. Such an atomistic view regards 'understanding' as a process of reducing the perceived complex situation into some understandable representation or description.

In addition, design cognition studies address that the designer cannot continue to work without understanding a specific context contained in design; most of the designer's intellectual abilities participate in this process and hence most design cognition occur here such as reasoning, understanding or learning. It is also for this process that many scientific design methods have been employed through design systems or computer programs.

However, paralleled with the nature of design problems that could not be decomposed into well-defined sub-atomic particles, designing is a variety-producing process rather than a variety-reducing process. That is, during design, the designer deals with amounts of varieties that are contained in a design situation, and develops them into a design product through compromising discrepancies between the varieties or discovering new varieties. In this process, the designer's professional skills, artistry, and tacit experience as well as pre-structured knowledge are exploited.

What is more problematic is that a design process entails a complete understanding of design problems. In the design process, the designer does not proceed design with a complete understanding but only with anticipations. Along with this process, the designer represents obscure design ideas in his mind and these design ideas are accomplished through exercising and developing imagination, knowledge or experience by design actions. Thus, design cannot be explained with a thinking or cognitive process alone, but it is understood as a process of making something, involving in actual actions. This observation is the starting point of a design thinking-action model.

4.2.2 Design Actions

Design Representations

Goel and Pirolli (1989) define design action as a process of the abstraction of design thinking and the representation of the designer's intention[13]. The design action includes lots of social activities, such as speech, writing, searching or drawing. Among them, the main design action is definitely drawing. Simply speaking, design is a result of working with various drawing such as sketches, diagrams, doodles, modelling, floor plans, or elevations. The designer externalises thoughts, not only as an end-product in the form of a design, but as an integral part of process itself in such drawing forms[14]. In this regard, Schön (1985) asserts that practising architects tend to value action over reflection[15]. That is, information, designer's experience and knowledge, or imagery all merge into these visual representations.

Design actions, therefore, have influence on all aspects of the design processes, involving analysis and evaluation of design problems (e.g., diagrammatic drawings), learning, generating ideas, as well as design thinking. Figure 4.2 shows the graphic expressions used in architectural design, classified according to the design three modes.

Each design mode has its own particular predominant expression of symbolic representation: the problem stage is usually involved in verbal modes (e.g., design brief, clients' demands), the design stage is executed mainly in non-verbal visual modes. And, the detail drawing stage uses iconic symbol system where the levels of abstraction are lower and the expressions more condensed and precise than other stages.

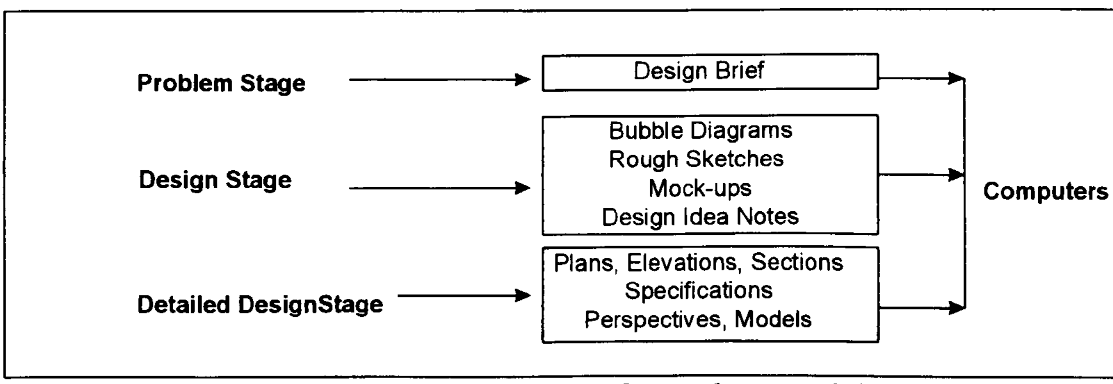

Figure 4.2: The particular expressions used in architectural design

Each drawing is employed for at least one, or for all of the following functions: (1) The means of communication a design idea to clients; (2) a method of studying building typology, using the analysis of existing examples; (3) the medium for testing the appearance of some imagined object[16]. While drawings in the problem or the detailed-drafting stage contribute to communicating with the client, constructors or other engineers, in the design mode, drawings are employed for communicating with the designer himself/herself, as a design tool for giving form, expressing visual image or storing design ideas. In this regard, the design action can be described in terms of a dialogue or play with a design situation[17].

Learning from Design Actions

We can experience that only after we engage in design action, unfamiliar situations become apparent, new problems are exposed, and the inconsistencies inherent in the formulation of the problem are revealed. This new recognition of the problem leads our understanding to be more refined and aids the designer to find more sophisticated strategies or to suggest new alternatives. The fundamental concepts of designing can be grasped only in the context of the doing – only through the experience of designing[18]. Thus, the designer engages in designing before a problem can be understood well enough to know what to do and how to solve it.

By drawing, therefore, the designer may gain new insights and progressively update the designer's understanding of the problems - namely a learning process. That is, by trial-and-error, designers come to learn more about the possible problems, strategies, skills or solutions, and expand the limits of their cognition. Thus, they learn from not only new information or knowledge but also by engaging in the exploratory design actions.

4.2.3 Thinking-Action in Design

Architects usually put their design ideas, whatever it is originated from intuitive inspiration or understanding of design problem, directly into design action. Any design ideas are, from the beginning, almost never suitable for immediate application for design solutions, and hence need a lot of additional work to refine them sufficiently. Through design actions, design ideas are defined and developed further into useful ideas or a valuable design by the aid of the designer's professional knowledge, experience or artistic gifts.

Therefore, the two activities - doing the thinking and design action - usually occur and develop simultaneously or consequently. Designers do not act after thinking; but in acting, they are thinking, anticipating and guessing the consequences of the action. In most design, thinking and action do not function separately but are complementary. Design thinking gives rise to design action by generating design ideas; design action makes design thinking visualised and realised symbolically by moulding the perceived problems into a holistic structure, or by forming mental pictures of a design in the mind.

With representing particular symbolic representations, designers continuously test and modify ideas and concepts; and negotiate their intentions with a given context, until feel satisfied as a whole. In addition, through drawings, they learn and discover new facts and new forms, and develop and create design values to an environment. It occurs in all of design process, even in the detailed design mode. Thus, design *thinking action* is the most significant phenomenon occurring in design activities.

We could take, for example, Le Corbusier's Villa Savoye. Here, on recognising design ideas to take shape, Le Corbusier immediately engaged in drawing in order to transcript his ideas into words, or to visualise them into pictures. It can be inferred from the figure 4-3 that design images in his mind are vague and ambiguous, but include most of the initial issues: appearance, ideas and intentions – open on all sides, orientation to the sun, ramp, solarium, and *pilotis*. And, these images are portrayed at a high level of abstraction, such as plans, sections and site plan of house.

His notion, "No more hesitations about playing architectural games with space and mass[19]", is a demonstrative example for the phenomenon of design thinking-action. In this process, drawings contribute to the synthesis of design thinking.

> "... one day, a spontaneous initiative of one's inner being takes shape, something clicks; you pick up a pencil... the drawing is useful only in contributing towards the synthesis of ideas already though out"[20].

Likewise, drawing in the architectural design process refers to the process of evolving design ideas, and transferring obscure images into a realistic feature by suggesting and evaluating numerous design ideas and alternatives. In playing such an architectural game, the architect can foster creativity, understanding of design problem, or the potential of imagination throughout– design actions.

From the introspective observation of the early design sketches, I can identify architects do not to begin generate ideas or images with apparent complete understanding of a design situation; rather, they continuously evolve and reconstruct the generated concepts or images, by engaging in design actions. In particular, the introspective study reveals that the designer's creativity depends much more on long, patient architectural efforts rather than solely on inspirational genius and in this process, drawings play significant roles in emerging new ideas and recognising new facts. In the next section, I will present the two salient features occurring in the design thinking-action - creative activity and visual thinking.

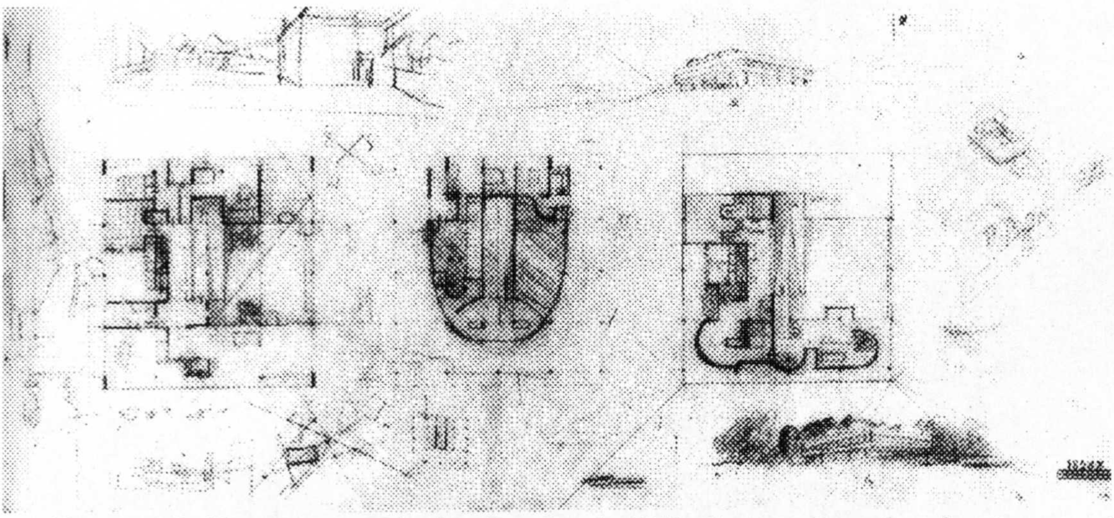

Figure 4-3: Numerous study sketches for the Villa Savoye. Pencil, colouring pencil and white chalk on sketching paper, Le Corbusier, autumn 1928, (from Curtis, p.12).

4.3 Two Salient Features of Design *Thinking-Action*

In the previous chapter, I have argued that architectural design is a making-something process distinguished from other cognitive processes and identified that its activity involves simultaneously in anticipation (thinking) and drawing (action). It is an open-ended process in which the designer expresses and exercises concepts, ideas and values; and one in which the designer discovers and learns new facts and relations. Designing, therefore, is not a series of decision-making or judgement events by a truth system; but is to propose and test assumptions, conjectures, or alternatives through design actions. The most distinctive features in design thinking/action from other cognitive processes are that this phenomenon appears in a *creative activity* and *visual thinking*.

4.3.1 Creative Activity

One significant feature of design is the designer's creative activity involved in thinking/action. To explain the creative process, we can go back Hadanard's well known four steps (1945): *preparation, incubation, illumination,* and *verification*, whose boundaries sometimes blur and which occur in different sequences[21]. Among them, the incubation and illumination stages play the most crucial roles in creative activities, and both stages are described as a 'dance of inner and outer' of conscious and unconscious thoughts[22]. Thus, those who are called creative architects may have the capability to manage to cope with the various design situations in the creative process or to absorb their inner ideas into outer reality through conscious design performance. In this regard, creativity is not a gift from God but the result of hard work requiring persistence, resoluteness, and commitment[23].

Any design task is subject to a given situation within a unique temporal and spatial context. The designer as a profession cannot avoid unpredictable situations and problems to be resolved, but ironically, they feel rather acceptable to them, because it is more difficult to create something new from a vacuum. Rather, the diversity of situations and constraints help designers to generate new, original ideas; activate their creativity; and give an opportunity to exercise their imaginations. Thus, the designer often experiences surprise at an unexpected outcome, which can be produced from the endeavour of dealing with the variables in the design contexts.

Moreover, a good design is clearly more than satisfying the client and a given situation; it involves imaging a building[24]. Architects endeavour to do something beyond the practical services that the users require and beyond the reconciliation between a situation and an adequate solution. In all design stages, they consciously attempt to furnish a special, new meaning and to say something new to and about our surroundings. The efforts to act and think creatively are essential to design activity, and involve an artistic mystique as well as the activities of problem solving process.

But, this creative activity is distinguished from artistic mystique. In fact, there exists no pure creative architecture. Architects do not invent architectural form, function or space; rather they try to create varieties to our environments within given conditions. Similarly, Rapport (1969) said, "The designer is not an innovator or form giver—he is rather the packager and modifier of form[25]". The effort to be different in a specific context is opposite to 'generalisation' that is a mainstream in the intellectual domains. What makes this activity different from others is that each designer has a different value system, in which they represent their own voices and interpretations to a context. Design is, therefore, likened to conjuring up a new life and a purpose on dead objects through the designer's own spells - their values.

Even though some designers claim that their products come from artistic gifts, designs cannot be accomplished without the creative efforts involved in thinking/action, in which design ideas are generated, developed and created into concrete configurations through experimenting, modelling and testing within a given situation. That is, any designer depends on much more the intentional creative endeavours than on unconscious inspiration, in the process of drawing out creative ideas. Thus, creativity becomes involved in the professional skills, experiences, imaginations, knowledge, or all together, which have been reserved potentially in the designer's mind. In this regard, design research on both design methods and design systems should focus on these creative efforts and to look to foster the designers' potential creativity.

4.3.2 Visual Thinking

While the creative efforts are required not only for designing but also for scientific discoveries and inventions, or for other human problem-solving activities, visual thinking is the most distinguished properties of designing from other everyday activities. As discussed in the previous chapter, architects directly visualise their thoughts without interpreting them into the verbal mode. Thus, the architect can be described as a non-linguistic thinker.

Architect as a Non-Linguistic Thinker

As discussed in section 2.2.3, there are many dichotomies in characterising the different modes in thinking. A typical form is the distinction between 'the thought with language' and 'that without language', along with different labels such as pictorial/propositional, non-verbal/verbal, or visual/lexical thinking, otherwise, intuitive/rational thought. Mounoud (1988) provides useful criteria to class the two functions in thinking:

> "Intuition thought and thought without language are supposed to function 'wholistically', apply to bounded, unspecified elements of a given situation, use success and failure as criteria, and be basically data-driven. Rational thought or thought with language, on the other hand, is supposed to function analytically, apply to unbounded, specified elements of a given situation, use truth and falsity as criteria, search for proof, and basically conceptually driven.[26]"

These different functions in thinking contribute to different goals: while thought without language is dedicated to the task related to immediate, direct adaptation to reality, thought with language engages in the task to understand, know and explain.[27] Design thinking/action definitely depends much more on the former thought mode than the latter.

That is, architects create and define the physical form of two or three-dimensional objects as a new environment in the mind, and they directly represent their visual thinking onto the drawing board through various drawing methods. As McKim (1980) has stated, visual thinking is greatly facilitated by representational procedures such drawing in a three-way interaction of seeing, imaging and drawing[28]. Most design process involve engagement in externalising the designer's visual thinking, such as concept drawing, diagrammatic and schematic drawing, modelling, or measured drafting. Rapport (1969) also identified that the designer thinks non-precisely and visually rather than verbally or symbolically[29]. In sum, architects make particular use of visual thinking[30] and hence they can be described as a typical non-linguistic thinker.

Cognitive Process and Visual Thinking

Design thinking is, therefore, to imagine visually how the design might to be. By engaging in design action, the designer transfers these mental images into physically realisable configurations. In this process, visual thinking plays a crucial role, and is the salient feature differentiating design thinking from other thought modes. That is, visual thinking allows us to see the holistic images of objects and motivates us to set about making mental picture into reality. Thus, these graphical modes of thought are central to designing and the making-something process.

Balchin (1972) named this mental ability as 'graphicacy' that characterises the human intellectual and practical abilities concerned with graphic and other non-verbal forms of understanding and communicating. Graphicacy is an equivalent concept to the other three, more generally-acknowledged, areas of human ability—articulacy, numeracy, and literacy[31]. It encompasses the ability to perceive and express inner objects though drawings, diagrams and modelling, which is neither involved in a verbal thinking mode, nor needs literacy; it is the most designerly of the abilities by which design idea gets turned into reality. Thus, an objective of architectural education and the architectural discipline aims to achieve such graphic, visual and spatial skills that play a crucial role in representing design thinking.

There have been attempts to explain such visual thinking as part of the cognition process in cognitive psychology and cognitive science. It is believed that visual images may act in the cognitive process together with lexical thinking, and that has provided strong evidence over the past two decades that the combination is used in performing many tasks[32]. Certainly, architects use images to solve and represent conceptual problems, especially those involved in the spatial relationships. For example, to answer the query 'how many windows there are in your living room', the solver may try to remember in the mind through visualising the room, or may draw the outline of living room onto paper, and then count the windows. These kinds of thinking-action processes occur very frequently during designing.

However, cognitive researchers focus much more on the cognitive image than the visual aspects[1]. While regarding visual thought as a primary or a pre-verbal process type of thinking, they consider lexical representation as being at a higher level in cognitive processes such as conceptualization and reasoning[33]. Furthermore, they argue that the content of images can be described in words and that therefore images can be organised as the cognitive schemata or frames that comprise knowledge[34]. Even though these approaches may make images amenable to the kinds of analyses that are commonly done in cognitive research, they cannot explain the design activities that are involved in visual mode of thinking and action.

For instance, Dewey (1950), quoted by Coyne (1991), asserts that visual images cannot be conveyed in terms of verbal language as follows.

> "Thinking directly in terms of colours, tones, images, is a different operation technically from thinking in words. But only superstition will hold that, because the meaning of paintings and symphonies cannot be translated into words, or that of poetry into prose, therefore thought is monopolised by the latter.[35]"

Thinking in words must wait until our mind abstracts or interprets an object, but design thinking immediately generates the act of into visualising mental images and

[1] Beach classifies the various images that people experience into three kinds such as visual images, mental images and cognitive images, see, Beach, L.R, *Image Theory: Decision-making in Personal and Organisational Contexts*, Wiley, Chichester, pp.16-17, 1990.

hence it has no time to wait for the abstracted words. In addition, visual thinking works holistically and it yields at once a whole image (verbal, visual or enacted) which is represented loosely. Such a holistic but non-precise, non-verbal and graphical mode of thought cannot be articulated by decompositional analysis or by verbal language. That may be the main reason why traditional cognitive theories have focused on the acquisition of verbal and numerical language systems, and have ignored or undervalued the non-verbal thought.

Especially, when the architect has pondered the concept of form, they should be involved in aesthetic (or perceptual) experience, such as order, balance, harmony or scale. Thus, the architectural form is embedded not only in the architect's cognition but also in perception. That is, the percepts of objects are organised as wholes in the mind, and the cognitive internalisation of perceived objects incorporate the meaning and significance that the architect assigns to the object[36]. Both cognition and perception function independently, but they are supplemental to one another in the architect's visual thinking. Accordingly, explanations of design thinking must necessarily involve the investigations of perceptual (aesthetic) experience.

Imagery theories in cognitive psychology have provided the valuable resources to explain perception, mental image and imagery. In the next chapter, I will introduce these imagery theories in order to account for perceptual process, mental images, imagery and imagination that are the most significant elements for designing, and will examine the functions of visual thought in design. With this established, I will approach a theory of *mental space* as a computational model for architectural design.

Reference

[1] Cross, N., 'Research in design thinking', in *Research in Design Thinking: Proceedings of Workshop*, Delft University Press, p. 9, 1991.

[2] Schöne, D.A., *The Reflective Practitioner*, Harper Collins, USA, 1983.

[3] Schöne, D.A., *The Design Studio: An Exploration of its Traditions and Potentials*, RIBA Publications Limited, 1985.

[4] Greene, J., *Memory, Thinking and Language: Topics in Cognitive Psychology*, Methuen, London, p. 159, 1987.

[5] Potter, N., *What Is a Designer: Things, Plan, Messages*, Hyphen Press, London, p. 72, 1989 (3rd ed.).

[6] Hawkes, D., 'The technical imagination: thoughts on the relation of technique and design in architecture', *The Journal of Architecture*, Vol.1, winter, pp. 335-346, 1996.

[7] Beheshti, R., 'Design decisions and uncertainty', *Design Studies*, Vol.14, No.1, p. 88, 1993.

[8] Greene, J., *Memory, Thinking and Language: Topics in Cognitive Psychology*, Methuen, London, 1987.

[9] Eastman, C.M., 'A data model for design knowledge', in *Knowledge-Based Computer-Aided Architectural Design*, G. Carrara and Y. E. Kalay (eds.), Elsevire, Amsterdam, pp. 95- 122, 1994.

[10] Goel, V and P. Pirolli, 'Design within information-processing theory: the design problem space, *AI Magazine*, spring, p. 34, 1989.

[11] Archer, L.B., 'Whatever become of design methodology?', *Design Studies*, Vol.1, No.1, pp. 17-18, 1979.

[12] Best, G., 'Method and intention in architectural design', in *Design methods in Architecture*, G. Broadbent and A. Ward (ed.), Lund Humphries Publishers, pp. 147-165, 1969.

[13] Goel, V. and P. Pirolli, *op. cit.*, pp. 31-33.

[14] Lawson, B., *How designers think*, Butterworth-Heinemann Ltd., Oxford, 1988.

[15] Schön, D.A., *The Design Studio, op.cit.*, p. 7, 1985.

[16] Edwards, W.B., *Understanding Architecture through Drawing*, E & FN Spon, London, p.1, 1994.

[17] Coyne, R. and A. Snodgrass, 'Is designing Mysterious? Challenging the dual knowledge thesis', *op. cit.*, pp. 124-131.

[18] Schön, D.A., *The Design Studio, op.cit.*, pp.55-56.

[19] Benton, T., 'Villa Savoye and the architect's practice', in *Drawings from the Le Corbusier Archive*, A. Tzonis (ed.), Architectural Design Editions Ltd., London, p. 9, 1986.

[20] Le Corbusier, *L'Atelier de la recherche patiente*, Paris, Vincent, p. 39, 1960, quoted by D.Pauly, 'The Chapel of Ronchamp', in *Drawings from the Le Corbusier Archive*, *op.cit.*, p. 36.

[21] Hadamard, J., *Psychology of Invention in the Mathematical Field*, Princeton University Press, Princeton, N.J., 1954.

[22] Evans, R. and P. Russell, *The Creative Manager*, Unwin, 1989.

[23] Allinson, K., *The Wild Card of Design*, Butterworth Architecture, Oxford, pp.189-196, 1993.

[24] Lason, M. S., *Behind the Post-Modern Façade: Architectural Change in Late Twentieth-Century America*, University of California Press, Barkeley, pp.165-166, 1995.

[25] Rapport, A., 'Facts and models', in *Design Methods in Architecture*, *op. cit.*, p. 137.

[26] Mounoud, P., 'The ontogenesis of different types of thought: language and motor behaviours as non-specific manifestations', in *Thought without Language*, L. Weiskrantz (ed.), Oxford Science Publications, New York, p. 27, 1988.

[27] Ibid., pp. 25-45.

[28] McKim, R.H., *Thinking Visually: A Strategy Manual for Problem Solving*, Wadsworth, 1980.

[29] Rapport, A., 'Facts and models', in *Design Methods in Architecture*, *op. cit.*, p. 145.

[30] Trovey, M., 'Thinking styles and modelling system', *Design Studies*, Vol.7, No.1, pp. 20-30, 1986.

[31] Balchin, W.G.V., 'Graphicacy', *Geography*, Vol. 57, pp. 185-195, 1972.

[32] Reed, S.K., *Cognition: Theory and Applications* (4ed.), Brooks/Cole Publishing Company, Pacific Grove, pp. 176-218, 1996.

[33] Beach, L.R., *Image Theory: Decision-Making in Personal and Organisational Contexts*, John Wiley & Sons, Chichester, pp. 16-17, 1990.

[34] Ibid., pp. 23-40.

[35] Dewey, J., *Art as Experience*, Minton Belch, New York, pp. 73-74, 1950, quoted by R. Coyne and A. Snodgrass, 'Is designing mysterious?', *op. cit.*, p. 130.

[36] Weber, R., *On the Aesthetic of Architecture: A Psychological Approach to the Structure and the Order of Perceived Architectural Space,* Avebury, Aldershot, 'Preface', 1995.

Chapter 5

A Theory of Mental Space

Abstract: *In the previous chapter, I identified a design phenomenon of thinking-action and its distinctive characteristics – creative activity and visual thinking. These properties cannot fully be explained by contemporary cognitive theories or the problem-solving paradigm. Thus, this chapter presents a new theoretical framework for the computation of design - a theory of mental space. It borrows fundamental ideas from imagery theories in cognitive psychology. I suggest a mental space model in which the designer's mind is analogised as spatial. This chapter also includes the study on the structures of mental space and its associated mental operations in the designer's mental space, which may give insights in developing an appropriate computer system for architectural design.*

CHAPTER 5: A THEORY OF MENTAL SPACE

In the previous sections, I suggested a new viewpoint of designing as a phenomenon – design thinking-action. However, questions still remain unsolved; what causes this phenomenon and what are the implications for the computation of design. Bijl (1989) states that "design refers to a human activity that takes place in the minds of the designer"[1]. Thus, the success of cognitive or computational models for CAAD depends on how profoundly and validly the designer's mental mechanisms and its associated mental operations are understood. With this as a goal, I try to establish a theoretical mental model for the computation of the design thinking-action phenomenon.

First of all, I clarify what is involved in these two different phenomena – internal operation (thinking) and external performance (action). The Cartesian mind-body dualism has divided the world into 'thinking substances'- the phenomena of mind; and 'extended substances' – the phenomena of bodies or matter[2]. From the viewpoint of dualism, the juxtaposition of the two terms seems awkward, somehow exclusive, in that while action is the phenomenon of bodies or events that are external and substantial, thinking is that of minds that is internal and subjective. In other words, the latter is physical phenomenon that can be seen and measured but the former still remains a mystery in modern philosophy and psychology.

However, I argued previously that both phenomena – design thinking and action - occur simultaneously and both are so intertwined that they cannot be explained separately by the mind-body distinction. Thus, to avoid such a dualism, I intent to follow the 'Double Aspect' viewpoint of the mind-body relationship, in which both mental states and bodily processes are interrelated[3]. In fact, our inner world and the external representation seem to be all mixed up in the sense that we live in our minds, and in turn, our feelings often get put into our bodies.

Furthermore, Morris and Hampson (1983), in their *conscious theory*, asserted that mental processes can be observable in a conscious experience as follows:

> "Mental processes are physical processes experienced *from the inside*... Brain processes are what are observable to someone examining the system, and conscious experience is what the system, when operating, feels like to itself.[4]"

This indicates that people are aware of some aspects of their mental process in a conscious status, and the mental experience can be reported from the bodily processes. The dual aspect theory and conscious theory help this thesis to avoid the problem of dualism, by denying that mental process has an existence independent of physical processes.

From this observation, this thesis premised designing as involving self-conscious activities and is a phenomenon that can be observed and explained. And, I identified in chapter 4 that design action can be seen as an inner experience reported during the design process, and this external expression may play a valuable part in understanding the designer's mental operations.

In addition, these theoretical backgrounds encourage this thesis to examine design thinking/action as one phenomenon, in which the mental processes have both an internal and external dimension. In parallel with the theoretical values, conscious theory gives insights into the computerising of a mental process, because the conscious process is close to the concept of the cognitive system whose activities in processing information, and determining and controlling behaviour can be observed.

Based on these theories, this thesis attempts to examine the designer's inner world in order to propose a new mental model and to establish a theoretical background for the computation of design thinking-action.

5.1 Mental Space: The Spatial Analogy of the Designer's Mind

Design can be seen as an intentional synthesis of material and forms in a way that can fulfil a specific purpose; and every activity involved contains the designer's intention, the purpose or meaning of objects. The term 'intentionally' distinguishes design activities from motor actions or artistic expressions. Thus, designing is often misinterpreted as a conscious problem-solving or a goal-oriented activity.

As seen in chapter 4, designing is distinguished from other cognitive processes, in that it is involved in visual thinking and the visualisation of images during solving a design problem. Its mental operations must retain different functions, mechanisms and properties from that of conceiving verbally.

However, mental experiences are not the things existing in the world but only exist in a virtual space somewhere in mind or the brain, so that we cannot have direct access to our mental operations. Accordingly, most efforts to explain mind have tried to treat it as if it were a special sort of matter – that is, by analogy or metaphor that is drawn from or linked to physics, biology, functionalism and systems theory[5]. Cognition research has attempted to remove some of mystery about how the human mind works by characterising cognitive processes, especially, in terms of the computational properties of information-processing mechanisms[6].

The advantage of modelling by analogy is that it makes a mental process more understandable by physically showing, manifesting, and displaying its mystified characteristics. Thus, this research starts with a hypothesis that designing takes place in *mental space,* where the mental operations involved in design thinking/action occur. The term 'mental' refers to the designer's inner conscious events or processes during designing, and that of 'space' refers to a hypothesized place accommodating the mental experiences.

The phrase 'mental space' is not a newly coined word. Even though not directly using this phrase, many cognitive theorists have suggested a similar concept of mental space, for example, Johnson-Laird's (1983) mental model[7], Kossyln's (1980) componential theory of imagery[8] or, significantly, Young's (1994) psycho-analytic study of *Mental Space*[9]. These three different but valuable concepts give me an inspiration to deal with design mental process through a spatial analogy.

Johnson-Laird (1983) argues that human beings understand the outside of the self by constructing a 'working model' of the phenomenon in their mind. That is, if we understand a fact or event, then we have a mental representation of it, which serves as a model of an entity in the same way as a clock functions as a model of the earth's rotation[10]. As a mental model mimics phenomena and objects in the outer world, it lists their elements, relations and operations in the inner mind. This is called the internal representation. This implies that there exists a system in our mind, in which the internal representation happens and causes this phenomenon. Thus, we can model the mind as a system that has its functions and structures.

Young (1994) suggests *mental space* as one of the ways we think about our inner world and human culture. He asserts that mental space is a place for reflection, for feeling, for having an experience; and that mental space is available as a container of experience, as it ruminates, metabolizes, savours, and reflects upon these experiences. As a psychoanalyst, he asserts that these concepts provide the parameters of the restriction and enhancement of mental space[11]. Though his research's direction is far from the inquiry about the mental process in designing, his way of explaining the operation of the mind is similar to the basic idea of this thesis. That is, both share the idea that mental space is not a tangible object, but that it is, nevertheless, conceivable and controllable.

But, the ideas of mental space are drawn out more directly from imagery theories in cognitive psychology, where these theories generally acknowledge the 'spatial' character of mental images, through a set of prototypical experimental findings such as mental scanning and mental rotation of images. Their basic assumption is that mental imagery constitutes a non-verbal working memory in which information may be pictorially represented and spatially transformed[12]. In addition, they suggest that images do not only represent the properties of imagined object, such as shape, size, colour and so on, but they also themselves have spatial qualities[13].

Pinker and Kosslyn (1978) have made clearer proposals about the spatial property of mental images:

> "... A property of images would be especially useful if images occurred in a three-dimensional structure, a kind of 'work space'. The space which we perceive and in which we move about is three-dimensional, and it surely would be useful to have an internal three-dimensional 'model' of space that we can manipulate mentally and in which the consequences of various contemplated actions can be visualised.[14]"

This spatial property of imagery implies that mental space (or work place) can offer an environment in which design images are represented, maintained, and manipulated. There would be little doubt that architects work within this two or three-dimension mental space during designing. For example, whenever design ideas or images take shape in the mind, architects immediately bring them into mental space; and when engaging in sketching or drawing, they experience themselves to be exploring and travelling in their mental space. The architect's tasks of are especially related to spatial representation – both internal and external - and thus they must have their own mental space, whose spatial extent depends on their experience, competence and graphical abilities.

For these reasons, I believe that the spatial analogy of the designer's mind can become a useful tool for understanding mental representation and mental operations in the design process. And, mental space can serve as a practical medium for examining the mental process and for computerising the designer's mind.

5.2 Imagery Theories and Mental Space

This thesis has argued that design thinking-action can be regarded as a continuous representation in the designer's mental space. Representation in design is not only the outcome of each design phase but also the instrument for generating design ideas and testing the success of the designer's intention through the interaction with various representations in the mind. And, in the previous chapter, I identified that most representations in the design process are mainly in the visual mode. Architects think visually and depict their thoughts in mental space; at the same time, they visualise or translate these images into drawings through graphic symbols. Thus, their thinking and actions depend on the visual sense modality, and this closely connects to images that are essential elements of visual thinking.

5.2.1 Design Studies and Imagery

Imagery in the information-processing paradigm is a controversial theme. The debate about imagery representation is ongoing, and the role of imagery in thinking and in problem-solving is still an open issue in cognitive science and psychology. Imagery is not directly observable and it is, therefore, so elusive. Moreover, it appears one moment and so quickly fades the next, that this limits the potential for objective, scientific experiments[15]. This subjective and transitory nature makes the research much difficult to discover the actual properties and associated functions.

Accordingly, despite its crucial role in the mental processes during designing, design studies have made little progress investigating imagery; rather, imagery has been relatively ignored as a 'black box process[16]', one that comes from the designer's mysterious mind. Meanwhile, research over the past decades in cognitive psychology has led us to recognising the existence of mental imagery as an executive controlling function in the mind, and has provided strong evidence that visual images are used in performing many problem-solving tasks.

Inspired by these experiments, some design protocol studies came to identify the existence of mental imagery in the design cognitive process, and a recent study on AI in design has investigated how images are utilised in computer programs[17]. Although the protocol data and computer models recognise the co-existence of verbal and visual conceptual representation in the human information processes, they have defined imagery as visual information in a conventional cognitive knowledge form or, at best, as an auxiliary cognitive medium of the verbal conceptual mode.

For example, Akin (1986) identified two basic modes in representation of designing through protocol analysis - the verbal-conceputal and visual modes. However, he gives these distinct modalities with the same functionalities, such as *production, conceptual inference structures, and chunk*, which become the operational elements of the verbal-conceputal mode in the context of a computer simulation[18].

Such explanations rarely includes the other mode - visual mode, which performs definitely different, crucial functions in the design information process, and thus it seems to be deficient to account for the designer's inner representation without this mode accounted for. Thus, the visual-thinking mode should be examined with a different approach from that of the verbal mode, because the different mode follows different properties, structures and functions in a particular mental mechanism.

In this chapter, I will review imagery theories to inquire about the designer's mental operations and processes. In doing so, I attempt to clarify the functions of imagery in the design process and to experiment with imagery theory as an alternative theoretical approach for CAAD research. Furthermore, I believe that this study can help establish the theoretical foundation for an alternative design computer model to the previous design cognitive models.

5.2.2 The Definitions of Image and Imagery

The definition of 'image' varies with its usage, ranging from the projection of visual scenes on the back of the retina[19] in visual science, to digital images displayed on a computer monitor in image process theories of computer science. In the more broad sense, the image is defined as 'the determinant of human all behaviours'[20], which is not related to visual or sensory image but to the image of one's self and of the goals, and which consists of value image, trajectory image and strategic image[21].

Such various definitions demonstrate that each research field has not only different convenient meanings but also focuses a particular feature of the image with different types of observations and methods for the scientific investigations. Thus, to avoid the confusion with the various meanings of words, I give definitions of certain words used in this thesis, such as image, mental image, imagery and imagination as follows.

- ***Image (or visual image)***: Images are commonly referred to as 'pictures in the mind's eye', internal pictures, or sometimes abstract imagery objects[22]. Images are separate and individual representations of sensuous and perceptual experience, in the absence of an external stimulus. Visual images refer to mental images represented in the manner of picture rather than language, and thus are distinguished from other auditory, gustatory, and kinesthetic images.
- ***Mental image***: Mental images are distinguished from physical images like paintings and photographs. Mental images are internal representations involved in mental imagery, which are "in a different space, do not have dimensions, and are subjective, are intentional, or even, in the end, just quasi-images[23]".
- ***Imagery***: Simply, imagery is described as collected different types of image experience, but in this thesis, imagery is particularly defined as the art of making images; and hence it is suggested as a crucial mental activity in the design process.
- ***Imagination***: It is used to denote the ability to create images via thinking or by intuition. In this thesis, it is distinguished from imagery: while imagery means the entire operation of image in association with other mental processes, imagination will be used to refer to the process which is opposed reality and reason in creative thinking.

5.2.3 Theories on Imagery

There are several suggested imagery theories in cognitive science and cognitive psychology. In this section, I introduce *dual coding theories*; *surface theories* and

Kosslyn's (1980) *componential theory* of imagery, which have provided this study on the designer's mental space with particularly valuable theoretical grounds.

Dual Coding Theories of Imagery

What are mental images like? Most imagery theories start with the inquiry into two distinct codes in ways to represent information; that is, pictorial code or descriptional code. Both the pictorialists and the descriptionalists agree that there are two different mental representation modes, but the latter thinks that all mental representation are descriptional, while the former thinks that at least some mental representations - mental images - are pictorial[24]. But, this debate remains still open.

The imagery debate is initiated from Pavio's (1975) dual code theory. As suggested by his extensive investigations, people remember and think about things that they have experienced with the aid of both *words* and *images*; and they may use two different codes – an imagery code and a verbal code – in order to store and retrieve information. Both are represented and processed in functionally independent, but are interconnected in that non-verbal information can be transformed into verbal information or *vice versa*[25].

He also claims that the dual-coding system is more effective in learning and memory, because it increases the probability that both imaginal and verbal process will play a mediational role in item retrieval[26]. He and his colleagues extensive experiments identified the evidence that pictures are much easier to remember than words, and that images are better than words for representing the way things look or appear; and that imaginal codes can enhance verbal recall and learning[27].

In this way, in addition to a verbal system, having a separate image system code would make it possible to recall information about physical objects in more flexible and powerful ways than can be encoded using explicit, verbal systems. Recent data of hemispheric differences provide further evidence for dual-code theory, which has suggested that the two cerebral hemispheres are differently suited for dealing with visual and verbal information[28].

More recently, the new imagery debates between the pictorialists and the descriptionalists has become more sophisticated. Their elaborate theories are endless and controversial; it is beyond the scope of this thesis to judge which theory is the better. But, it can be said that these theories have contributed to removing some of the mystery of human mind and have provided rich evidence of the existence of a visual mode in thinking and representation. Next, I will review *surface representation* theories that furnish important ideas in developing a theory of mental space.

The Surface Representation Theory

Bourne *et al.* (1979) classified the theories on imagery representation into three categories: picture-analogy theories; symbolic representation theories; and surface representation theories. The first category assumes that when a person uses imagery to memorise some material, that material is converted to mental pictures that are stored and later retrieved; symbolic theories posit that the representations underlying images are not different from those underlying verbal material. Accordingly, both image and verbal representation could potentially be encoded in the common language of the computer program. *Surface representation* theories that have been developed by the pictorialists believe that images are thought to be generated in short-term memory, and once generated, their surface representation can be analysed[29].

That is, the former two theories suppose that mental imagery constitutes an elaborate form of coding in long-term memory; the image can be generated by simply retrieval of stored information; and thus these phenomena can be operated on by a computer program. Meanwhile, surface representation theories suggest that images are not stored holistically in long-term memory, but are simply 'activated' when one experiences a surface image; that is, once an image has been retrieved or constructed, it is referred to as a 'surface image' or 'an image held in active memory'[30].

Richardson (1980) described these theoretical distinctions as the *constructive* and the *elaborative* uses of mental imagery[31]. And, he pointed out the change of research concerns with from long-term memory to immediate memory by quoting Anderson's (1978) notion:

> Most of the original research on the nature and function of mental imagery was concerned with its elaborative role in long term memory, but more recently a 'second generation' of experimental research has been concerned with operations on mental images in immediate memory[32].

Imagery also has a function to play in cognition by virtue of the fact that it possesses or manifests properties that cannot be deduced from a more abstract, underlying long-term representations. Such properties have been reported following psychological experiments. For example, Kosslyn (1973) demonstrates through his image-scanning test that images depict information in a quasi-pictorial way that allows them to be scanned such that scanning time increases with distance travelled[33]. This might include the possibility that the active image can be scanned or inspected in a manner analogous to the scanning of real objects, or that the image functions as a mental model which can be rotated, re-scaled and otherwise transformed[34].

The results of such experiments indicate that mental imagery can be employed in the representation, preservation and manipulation of spatial and pictorial information. In addition, imagery can be used to make explicit information that was previously tacit and they can be constructed, re-constructed, even modified by activating different parts of the long-term database.

Surface imagery theories provide very important evidence for the existence of mental space, in which imagery functions as a form of short-term working memory. Moreover, they imply that mental space can be operated by its own parameters (imagery or knowledge) independent of a long-term memory system. This will be discussed in chapter 6.

Componential Theory of Imagery

Imagery theories generally accept the hypothesis that mental imagery shares information-processing mechanisms with visual perception: much of the experimental literature on imagery theories has showed that perceptual phenomena have been found to occur with imagery and hence the representations of imagery and perception are of the same kind[35]. Accordingly, some imagery research has attempted to account for the structure and process of imagery, in the way that perception (or imagery) information transforms between the stimulus and the response in performing a task.

Kosslyn, in *Image and Mind* (1980), has provided a comprehensive and general componential theory of imagery, consisting of information-bearing structure and information-manipulating processes in a *visual buffer*. He suggests that images have two major components: the surface representation and the deep representation as follows:

> "The *surface representation* is the quasi-pictorial entity in active memory that is accompanied by the experience of 'having an image'. The *deep representation* is the information in long-term memory from which the surface image is derived[36]."

Based on two sorts of representation underlying images, he proposes a protomodel and distinguishes between short-term (active) memory and long-term memory. Below figure 5-1 shows the structure and process of visual imagery as adapted by Farah (1986).

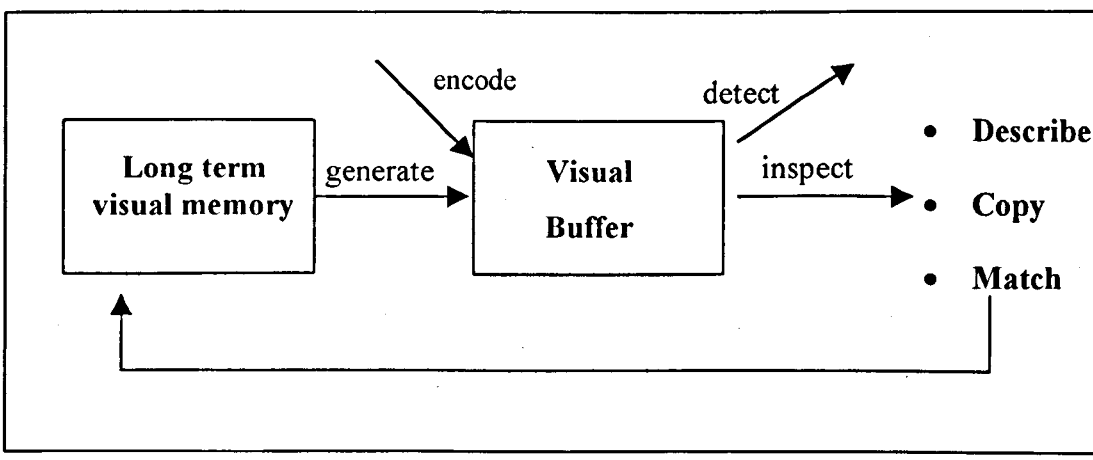

Figure 5.1: Schematic diagram of the stores and processes involved in visual imagery and visual perception. (M. Farah[37], p. 250)

Kosslyn (1980) called the short-term structure the 'visual buffer', which is not itself information-bearing but is the medium of mental imagery within which images are constructed and manipulated. It is explicitly spatial, as the visual buffer functions as if it were a coordinate space or array of locations. Within long-term memory, there are lists of facts about objects and storage of the appearances of objects, which he describes as representing the *literal* appearance and describing a thing. He suggests that the literal memory component contains representations that underlie the quasi-pictorial experience of imaging, and the propositional component consists of list-like structures.[38]

Parallelled with the imagery structures, Kosslyn proposes a number of imagery procedures that act upon the long-term memory representations and the visual buffer. His theory describes three basic sorts of image processes as follows:

> *Generation* processes create an image in the visual buffer from information in long-term memory; *inspection* processes operate on the visual buffer to encode relationships and identify parts within the visual image; and, *transformation* processes can transform (e.g., rotate, translate) a visual image within the coordinate space (visual buffer)[39].

According to this model, imagery shares many of the same representations and processes as visual perception. When an object is seen, its appearance is encoded from the retinal image into the visual buffer. It may then be matched to one of the appearance stored in long-term memory and the cycle is repeated until the object is identified. Once the imaged objects are formed, they can be inspected using the same internal processing that is used during perception[40]. That is, when an object is imagined, its appearance is generated from the long-term memory into the visual buffer. Whatever seen or imagined, the contents of the visual buffer can be inspected or transformed in order to match with a pattern or to answer a question.

In this way, the inspection process organises and transmits the information displayed in the visual buffer to other cognitive systems. This process may yield the structured patterns of activation for further processing. Farah (1986) added this new feature to the Kosslyn's protomodel for a task analysis:

> "a '*describe*' component for question-answering tasks in which the contents of the visual buffer must be inspected and described; a '*copy*' component for constructional tasks in which the contents of the visual buffer must be inspected and drawn or constructed; and '*detect*' component for simple visual perception tasks and imagery introspection task.[41]"

Her neurological analysis provided evidence that the long-term visual memories used in imagery are also used in copying or recognition tasks. The task of designing is, however, a more complex task than that of copying. It is a more complex perceptual sensory task. Consequently, based on the literature reviews on imagery theories, I will examine the structure of the designer's mental space and the mental operations occurring during design in the next section.

5.3 A Mental Space Model

As discussed in the previous chapter, design thinking-action refers to a phenomenon that occurs in the designer's mind. The research on the designer's mental processing mechanism may be, therefore, valuable to understand its phenomena, to conceive physically computer-aided designing, and to establish a design model for the computation of designing.

However, the deep, precise study of the structures and processes of human mind is beyond the scope of this research. In particular, designing requires more complex mental operations than the recognition or recall tasks like 'how many windows are there in your living room', or the spatial tasks used in imagery experiments like mental rotations and mental scanning.

In addition, designing is an activity, aiming at making something. Such properties of designing lead to investigation of the designer's external representation as well as internal representation in memory. Thus, this research focuses on the mental operations not only in design thinking but also in design actions rather than general psychological issues, such as the mental representation or the relationships between perception and imagery.

Before discussing the structure of mental space, I should make clear the meaning of image or imagery used in a theory of mental space. As defined in section 5.2.1, images are generally viewed as separate and individual representations of a perceptual experience, in the absence of an external stimulus. It is commonly accepted that an image is a representation of something that *resembles* what it represents[42], or analogous to the experience of seeing an object during visual perception[43].

In particular, in this thesis, images are regarded as a symbolic representation in mental space or memory, and they always have at least one quality or characteristic of shape, form, name or colour in common with what it represents, in two or three dimensions. Meanwhile, imagery is regarded as the mental activities or phenomena of generating and manipulating images and thus it can be used to aid conscious thinking and design problem-solving.

5.3.1 The Designer's Mind – Mental Space

In this thesis, the designer's mind is analogised as what is spatial; where design ideas are generated and developed – as *mental space*. Such a spatial metaphor has been often employed in design theories or by designers, for example, 'the designer as a black box or a glass box[i]' or Le Corbusier's notions: "the human brain is like a 'box' in which one lets the 'elements of a problem' simmer"[44].

Mental space has the properties of territoriality and being. Firstly, where does the mental space exist? The thesis suggests that it may be located somewhere in the mind between me and the external world, and thus may be neither subjective nor objective but occupying both realms. It seems to be one of the '*transitional phenomena*' that exists between there being nothing but me and there being objects, and between or both the internal reality and the external world[45].

Apparently, the designer's mind can be supposed as the transitional realm, in the sense that the objects dealt with in the mental space are neither real building nor non-existent objects, and design activities engage in transferring inner intention into the reality as a design. From this, I suggest that mental space exist somewhere in the design's mind as a medium linking between inner thinking and the outer expression. This implies the significant role of computers in the design computational processes. That is, the computer in designing should serve as a medium transferring design thoughts to appropriate design actions smoothly and seamlessly.

Secondly, what does the mental space look like? It does not seem that mental space is nothingness; and it is unclear whether mental space has Cartesian coordinates as seen in many CAD applications. Mental space may contain its own, certain components and operations. And, it seems to have neither rigidly defined boundaries nor limits in spatial extent. Rather, it has no fixed area or dimensions so that information moves freely between two and three dimensions, and even the time-dimension. From this, it is inferred that architects may have a more extensive mental space than other professions, and that it can be extended by design education and practice.

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[i] Jones (1969) classified the designer's brain as a black box and a glass box: the former is out of reach of the conscious control and thus mysterious, but the latter can be discerned a completely explicable rational process.

5.3.2 The Structure of Mental Space

This thesis posits that designing takes place in the designer's mental space and this can be observed through an analogy; take the following hypothesised scenario.

> *Architects usually start to bring design ideas on mental space. These ideas are compared or inspected with the remembered experience in long-term memory. When an image related to the ideas appears in mental space, they can see a picture (or picture-like representation) of objects or events through their mind's eye. Then, they manipulate, modify, or create mental images (design thinking) and at the same time they draw or copy these images on a drawing (design action). This process will be continued until they are satisfied that they have reached an interim goal.*

In order to account for the mental operations involved in this design process, I suggest a simple mental model that decomposes the mental structure into three different systems: memory system as information bearing; mental space as a information operating system; and the interface system between mental space and memory (see, *figure 5.2*). The memory system retains information about design in the forms of semantics or pictures. Mental space is a working place in which the design mental operations – such as generating, designing and visualising - occur. An interface exists between the memory system and mental space, which functions as an attention system or the designer's value system.

Mental space may share some similar mental processing mechanisms with imagery systems discussed in section 5.2, such as visual working memory[46], visual buffer or mental models. Both mental space and imagery systems are a spatial metaphor of the human brain; and perform as if they were a physical space. They function as a working-medium in which design or image representations and can act independently of long-term memory.

However, even though the concept of imagery systems provides the foundations for a theory of mental space, the designer's mental space may have different functions and structures from them. Thus, the scope of the research in this thesis is limited to an examination of the designer's mental structure, functions, and its associated operations rather than one of a general model of the human mind. Below its structure will be discussed in detail.

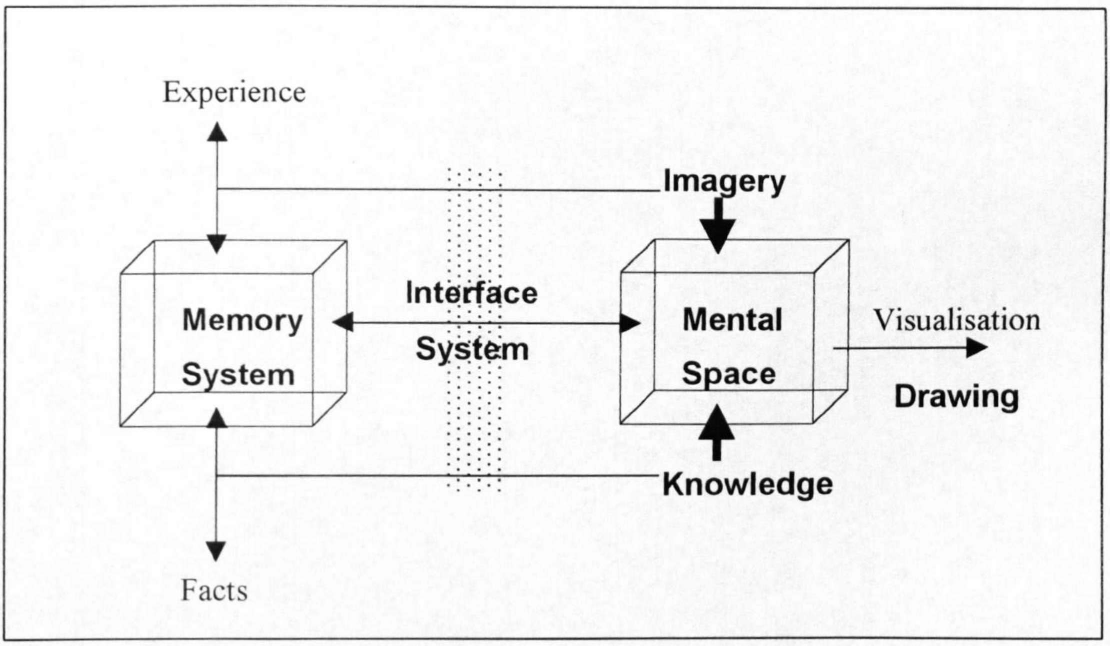


Figure 5.2: A hypothetical mental model: the general structure and the components of mental model.

5.3.3 Memory System

In the theory describe above, the mental structure embodies three sorts of systems – the memory system, mental space, and interface. Here, the memory system holds the designer's repertoire, and functions to store design information from fact and experience and then distributes information or knowledge to mental space.

Most memory systems share the assumption that whenever we are thinking about a problem or imagining an event, we use some stored information in the forms of verbal code or visual code, or both. Thus, what kinds of information store, and how they can be stored and retrieved from memory are the main concerns of the information-related fields. Next, I will examine the information used during design and representation in memory.

Facts and Design Experiences

Information theory has generally defined 'information' as 'data that has been processed into a form that is meaningful to the recipient's actions or decisions'[47]. Lera (1982) articulates the information that has an influence on the design activity such as regulations, technical information, published precedents, stereotype solutions and imaginary, self-imposed goals, rules of thumb, simulations and so on.[48] A design activity needs information in different forms at the different stages of the design process.

Paralleled with many sources of outer information, the design activity involves the cognitive process requiring the designer's inner knowledge. Each designer has their own repertoire, and each finds information from experience or facts relating to the outer world, which are functions of knowledge, mental habits, and education. Thus, they have their own ways to organise memory and retrieve information.

In particular, some activities in designing appear in a subconscious way, and the designer only becomes conscious of information when questioned 'why', or 'how'. There appears to be a 'tacit knowing' described by Polanyi (1962), as 'there are things that we know but cannot tell'[49]. From this, Cross (1981) classified the knowing status in the design process into two categories: *knowing how* and *knowing that.*

> Firstly, *knowing that* is not of necessary part of design. Theory may not be all that helpful, that is, knowledge of the explicit 'rules' of design can actually inhibit practice. The focus of attention can be in the wrong domain – in the explicit procedures rather than the subtle details of performance... Secondly, *knowing how* i.e. the inexplicit, manipulative non-verbal acts of skill, lies at the core of design.[50]

While *knowing that* derives from the truth, the facts or the rules, *knowing how* derives from the architect's experience, the use of metaphor and analogy, or the assimilation of examples both from the present and the past. Historically the designer's crafts and skills come from this *know-how*, which plays a crucial role in designing.

Thus, in practice designers depend much more on their own professional experience rather than the structured information or knowledge. Faced with a new problem in an unfamiliar situation, they do not start from scratch, rather they interpret the new context by the metaphor of a similar experience from previous experience. In this context, experience makes the tacit knowing of architecture a feasible reality[51]. It thereby enables an obscure knowing to become concrete through drawings; and often enables design ideas to emerge simply without significant effort. Thus, the more competent designers have more *know-how* and more ability to associate a new problem or situation to learned events, concepts and values.

While the memory components related to facts can be easily externalised as significant information in the cognitive process, those related to designers' experience - such as aesthetic[ii], episodic, tacit-knowledge, or know-how memory – are too vague to be articulated by verbal codes. Thus, design information is only ever partially explicit; the rest remains non-verbal. The proposal arising from all this is that the design experience be represented in the form of imagery, while facts are represented as conceptual structures or knowledge chunks in the memory system.

Representations in the Memory System

In the above section, I discussed what kind information is used in the design process, and identified the different sorts of information, the knowing, and knowledge. This section describes how they are represented in the memory system.

When the designer imagines or reasons something, it can be supposed that some images or concepts are evoked from memory and then they appear in mental space in some particular format. Here, different information is represented in a different mode. Tulving (1972), in *Organisation of Memory,* classified these memory representation modes into *episodic* and *semantic* memory as follows:

> "Episodic memory receives and stores information about temporally dated episodes or events, and temporal-spatial relations among these events... Semantic memory is the memory necessary for the use of language. It is a mental thesaurus, organised knowledge a person possesses about words and other verbal symbols, their meaning and referents, about relations among them, and about rules, formulas, and algorithms for the manipulation of these symbols, concepts and relations[52]."

That is, episodic memory contains information about our personal life *experience* associated with a particular time and place; semantic memory contains information about the *facts.*

The semantic format is a strong method in the sense that great precision may be achieved in the form of explicit description, and thus it is easily manipulated and

[ii] Moles (1966) proposed that there exist two types of information that we deal with - *semantic* information and *aesthetic* information. While semantic information having a universal logic, structured, articultable, and translatable into a language, prepares acts, forms of action, aesthetic information is not translatable, and it is only approximately transposable, that is, it has only equivalents, not equals.

contains the full range of computational operations within its potential. These kinds of memory systems are characterised, as Anderson (1978) stated, that (1) they are abstract, (2) they have an explicit set of rules or a syntax determining well-formedness, and (3) their symbols have truth values[53]. Actually, the existing knowledge-based engines implement these memory systems by expressing, linguistically, facts such as rules, principles or regulations.

However, new findings in imagery theories indicate that other types of representation in memory – the mental image - may be just as important as verbal information. In contrast to the verbal concept, the mental image is a pictorial symbol representation, containing information about appearance, shape or location of physical objects or events. Pictorial symbols resemble (or look like, or share properties with) what they represent.

For example, the answer to the question "how many windows are there in your living room?" - such information cannot be listed as an explicit proposition in memory, but it is stored as an implicit visual perceptual mode in memory. If there are routines analogous to the ones that can recognise these properties from visual input, then these routes can also recognise them from information stored in memory that is similar to the visual input. Thus, a mental image is defined as a spatial representation analogous to the experience of seeing an object during visual perception[54].

From this, the memory system that the architect employs during design process functions in the manner of an imagery system that is specialised for encoding, storing, organising, transforming, and retrieving information concerning concrete objects and events[55]. It is distinguished from the other (verbal) system that is specialised for dealing with information involving discrete linguistic units and structures.

Unlike perceptual experiences, we often imagine non-existent objects or events in the absence of an external stimulus. In such cases, there will be no readily available referent for the image to correspond in memory. The mental image can be used to tell us about a general class of objects but cannot represent any one specific property of class: that is, it may display a *prototypical average* that best informs us about the object as a whole[56]. Thus, mental images are more ambiguous, less easily manipulated; and hence they are difficult to be computerised.

Moreover, design memories are accumulated through one's experiences that occur at some time and in some place. They depend on and vary with a specific design situation rather than on item-specific properties for the memory trace. Thus, they cannot be reduced in ways to be classified or structured. These facts increase the difficulty of computerising the graphic mode in design memory. Accordingly, an interactive form of image in a computer is impractical until an appropriate graphical language is developed[57].

5.3.4 Interface between Memory and Mental Space

The designer uses a wide range of forms of information - skills, know-how, intuitive knowing and knowing derived from design action, as well as the structured knowledge. These cannot be easily formalised and pre-structured in the memory system as a propositional format. It is identified that the designer uses visual images during designing, and the images exist as a main phenomenon in mental events, states of consciousness and experience, which produce effect on the physical design action.

From this observation, I doubt the assumption that all information is preserved as modality-specific memory codes in a separate part of the brain. This assumption has been reinforced by the recent results of neuropsychological research that provide strong evidence for the functional dissociation of the two cerebral hemispheres with respect to the processing of verbal and non-verbal information[58].

However, even if the mental processes can be classified as two significant modes, there still remains a question about the dual coding system that is an underlying mechanism of the memory system: each of the verbal and visual representations has different modality and specific functions, and each is even processed independently. The suggestion that two independent modes exist in separate part of the brain can be questioned.

Here, I exemplify a simple architect's design activity as follows:

> *Imagine the architect's mind that receives a request form the client for a 'comfortable' space. What appears in architects' mental space? Some architects*

may conjure up a certain objects and events such as a room, a chair or environment from each past perceptual or actual design experience, or some may remember a case or a fact such as the relation of 'if-then' from their accumulated brief systems. Both two representations may come from the same schema in memory, labelled as "comfortable".

This example denotes that images are constructed in response to words as stimuli, regardless of any specific properties of those images, and it makes clear that there exist two different mechanisms in the mental process, in that some depend on pictorial modality and some on descriptional one - dual modality-specific processing. However, research has not yet fully resolved how the abstract words ('comfortable') evoke the concrete visual images or whether these images are stored as a picture-like (visual image) or a word structure (schemata) in memory.

Moreover, the hypothesis that information is stored in the brain separately in two different formats is much more controversial. In the example above, the architect draws out design ideas and images – either visual or verbal - from the same place in the memory system, that is labelled as a word like 'comfortable', or as a concrete object, like 'a chair'.

Mole (1966) stated that there exists no information with exclusively semantic or purely aesthetic content; the two types are simultaneously and progressively reduced from the initial symbols, while interacting with each other[59]. This process involves mutual compensation and helping each other as a way of apprehending a problem. Foder (1981) justifies this argument by demonstrating the example of maps as follows:

> Many representations have elements of both. For his example, maps are pictorial in respect of some of the information they convey like geographical relations, but they are non-pictorial in respect of other information like population densities or elevations[60].

Even though the designing and making a map have different processes, the products of them have similar contents of information – objects and its relationships. Thus, it is identified that there are different types of descriptional representations and different types of pictorial representations, although there may be representations including both.

From this observation, I suggest that the information involved in designing be encoded in memory in a multiple way: randomly and inclusively. When a memory component is needed, it changes into the appropriate formats at the *interface* of the designer's mind, regardless of the form of storage in long-term memory. That is, the designer is accustomed to dealing with retrieving information from memory and thus retrieval is performed in the almost unconscious ways. Thus, the more competent architect can employ deftly design resources without deep inspections of memory, and can change the memory components into appropriate forms to a design situation without a conscious effort.

It is also suggested that the interface of the designer's mind serves as a connector between memory and mental space. The interface system may function to activate the memory system responding to outer information; to distribute a memory source into mental space in an appropriate form; or transfer the useful information in mental space into the memory system for later uses. It seems to work similarly to the 'attention system' that is defined as 'the source of interest on the subject[61]'. Because, the mental process will differ in ways that the designer posits the functional significance – that is, attention. This value-laden system may exist between memory and mental space, and it affects the ways that the designer thinks, deals with the world and makes a design decision. Because of these nebulous qualities, it will almost certainly remain in the human domain since these qualities cannot easily be mimicked in computers.

The arguments above may give some implications for developing a future computer system for architectural design. I believe that the memory-based system will become less critical issue in CAAD research. Thus, this thesis suggests a mental space model as a metaphor of the designer's mind rather than a memory model, and it focuses on the designer's mental process and representation in mental space rather than on the organisation and representation in memory systems. The following section will discuss the mental operations that occur in mental space during designing.

5.3.5 The Mental Operations in Mental Space

In this thesis, mental space is analogised as an instrument for accommodating the design thinking-action in a two- or three-dimensional structure. In mental space the designer draws mentally design ideas and concepts; shapes a form and a space; and tests design ideas or images. These are engaged principally in perceptual mode, and their thinking is characterised as visual thinking.

In this way, the designer depends much more on a seeing ability than a conceiving ability for understanding. Because of its visual, perceptual properties, the designer's mental space maintains similar structures and properties to the imagery system that is one of the representational media used in perception.

Even so, mental space has some distinguishing features from the memory or perception. That is, mental images in mental space are based neither entirely on immediately perceivable properties nor are they generated entirely through the action of memory and higher interpretative processes. While perception is an *autonomous* process by which environment stimuli are organised into specific form[62], mental imagery in mental space is a *deliberated* (conscious) process by which the percept becomes a meaningful image for a design. In addition, mental space does not take part in the process of transferring from percepts to memory, and is involved only minimally in encoding and organising a memory. But instead, it is used a forum where design ideas – whether in visual or verbal format- are reconstructed from a remembered experience which are then changed into a concrete design[iii].

In this context, the newly constructed ideas in mental space are distinguished from the remembered images in a memory system. Moreover, both are often represented by their distinct type and contents. Mental space has therefore its own functional value in the design process, which activates design thinking and drawing independently of the memory system. The mental operations can be described as three main design mental activities - generating design ideas; designing in mental space; and visualising mental images, which are interrelated with each other and occur at the same time.

[iii] Morris and Hampson (1983) have suggested two types representation – a new construction (imagination image) or a remembered experience (memory image): While imagination images must draw on memory information, a remembered experience will represent a reconstruction rather than an accurate reproduction of the visual images.(Morris, P.E. and P.J. Hampson, *Imagery and Consciousness*, Academic Press, London, p. 67, 1983)

Generating Design Ideas

Generally, design starts with generating design ideas or forming design concepts. Both 'idea' and 'concept' are equally defined as 'what is understood by a term, particularly a predicate', but the term idea is associated much more with subjective mental imagery which may be irrelevant to the possession of a concept[63]. Thus, the term 'idea' is more flexible and suitable for explaining a design thinking that involves both the visual and verbal modes. In this thesis, design ideas refer to new concepts, possible solution to a design problem, or new meanings in a design situation.

Generating ideas is distinguished from the process of retrieving information. The retrieval process includes recall (verbal) and recognition (visual)[64], and it connects a new problem with information retained in the memory system. However, most design information – basically derived from design experience - is so implicitly, loosely encoded in memory that it is recognised in an obscure, imperfect or indeterminate form. On the other hand, design ideas would float to the surface of mental space where they could be caught, condensed and externalised as drawings. Thus design ideas are more concrete, vivid, holistic and context-related than simply retrieved information.

Generating ideas is the most creative phase in a design process. It is said that a design idea is generated from two opposite resources: (1) by intuitive leap and artistic imagination, or (2) from the understanding of a situation. The former views regard creativity as a mystery process and the latter is the cognitive viewpoint.

However, a design idea does not occur from either of them but must be involved in both mental processes. Eder (1995) observes that creativity, generating novel ideas, occurs as a result of the oscillatory interaction between the intuitive (erratic, inconstant, non-calculable) and the intellectual (systematic, methodological, analytical)[65]—both motivate, stimulate, and help each other to generate a design idea. Thus, during this phase of gestation, the spontaneous design ideas take shape and their references come into play in the process of the creation of the architectural work.

That is, even though most new ideas are generated by artistic and intuitive imagination, they do not arise from a vacuum but always appear in the course of saturating oneself with the situation and by understanding the relevant facts. Accordingly, as mentioned in section 4.3, design ideas are obtained much more from the creative efforts and the creative manner of thought or the technique of invention dealing with a certain task, rather than the subconscious 'dream state[66]'.

Designing in Mental Space

Whenever ideas or images float to the surface of mental space, the designer immediately brings them into mental space mainly with a pictorial format. The designer experiences this perception as a phenomenon that can be seen via the mind's eyes. In addition to seeing, the good designer, unlike laymen, copies or depicts deftly these mental features as a design element

But, the mind does not always produce a design immediately. The designer progressively develops design ideas into a more vivid design or into clearer understanding of the problems that need to be solved. Much of the information that is used in its development evolves through the adaptation, refinement and combination of the generated ideas. In this context, the design ideas can be regarded as preinventive forms in the creative process (Finke, 1990). That is, preinventive forms are generated by combining parts and figuring out how to use the invented object through the cycle of exploration[67]. Thus, the preinventive images become the precursors to the final creative product.

In a similar vein, Ullman (1984) argues that a visual recognition is solved by routines that can add information to the visual input, yielding 'incremental representations'[68]. In this way, a design is condensed and accomplished in mental space, as the designer exercises initial images and concepts and then discovers and adds new facts and create forms to them. Thus, it is suggested that *designing in mental space* is a process through which the design representation gradually evolves from something obscure into the concrete and the refined.

Whether the initial information is a verbal descriptive one (e.g., design briefs, documents or talks with clients) or a pictorial one (e.g., visual experiences or drawings), the designer converts them into pictures in the mind through the a perceptual process; and then they visualise these mental pictures through the design action –drawings and modelling. That is, what the designer explores in mental space is conducted and actualised through visualising the mental features on a drawing board.

It can be said that the former is *internal representation*, whereas the latter is *external visualisation* that is a kind of motor action following internal representation. In mental space, both representations occur simultaneously as do design thinking and action. This enquiry verifies a main argument in this thesis: that is, designing must be treated as one phenomenon – thinking/action (chapter 4); or mental space is a transitional realm that links inner thinking and the outward expression resulting from that thinking (section 5.3).

The next question is about designing as a self-conscious mental process, which is a basic premise in this thesis. The mental process of designing cannot be seen and it is too fast to recognise with consciousness. Thus, much literature in the design domain has regarded designing as an intuition-dependent process or a non-cognitive process. At a glance, this may be the case. Even though some design ideas pop into the mind unexpectedly or unconsciously, most of them are related to mental operations which the mind has absorbed through experience of an associated design situation. It is for these reasons that if they did not *see* and *know* the designer cannot *imagine* and *think*[69].

In other words, as the designer has become accustomed with the experiences of representing in mental space through accumulated practices, the associated mental performances become automatised and hence they appear to be unconscious. This observation can justify the assumption that designing (or the mental process of designing) is involved in self-concious activities. Dennet (1981) also argues that everything that we *can* know about via seeing *always* 'presents to consciousness' as a stable picture[70]. That is, designing in mental space refers to the designer's conscious representation of mental images; and those images are recalled, when needed, in a clear and consistent form.

Visualising Mental Images

Most importantly in designing, drawing in mental space occurs alongside drawing real images on the drawing board. That is, the internal representation and the external visualisation partake in designing at the same time. The ability in visualising and manipulating mental images differs according to what experience and ability one has. Thus, a good designer is able to readily recognise and visualise objects from the mind on paper. Without drawing, the designer would find it difficult to develop his/her thinking and even design itself.

Drawing, in the design process, is a very special sort of drawing. It is different from the polished and final description of the completed design, and is a means for designing. Drawing on paper is regarded as an extension of the internal mental space. Thus, it is not communicative in the wider sense, but serves to communicate with the designer himself/herself. In this regard, Schön (1993) has argued that we should think of the designing as having conversation with the drawing[71].

Van Sommers (1984) examines the mental operations involved in the drawing process through a psychological experiment on 'how a drawer proceeds from instruction to a graphic product' as follows:

> "The linguistic description of what is to be drawn is decoded and results in some perceptual-cognitive representation in the mind of the subject, perhaps in the form of an image or some other quasi-spatial scheme. The subject then simply puts into operation a set of graphic skills and procedures to represent this scheme as a drawing.[72]"

He refers to drawings as the presentation of internal representations of objects by executive processes of production. Thus, drawings are considered as the visualisation of images in the drawer's mind using graphic ability.

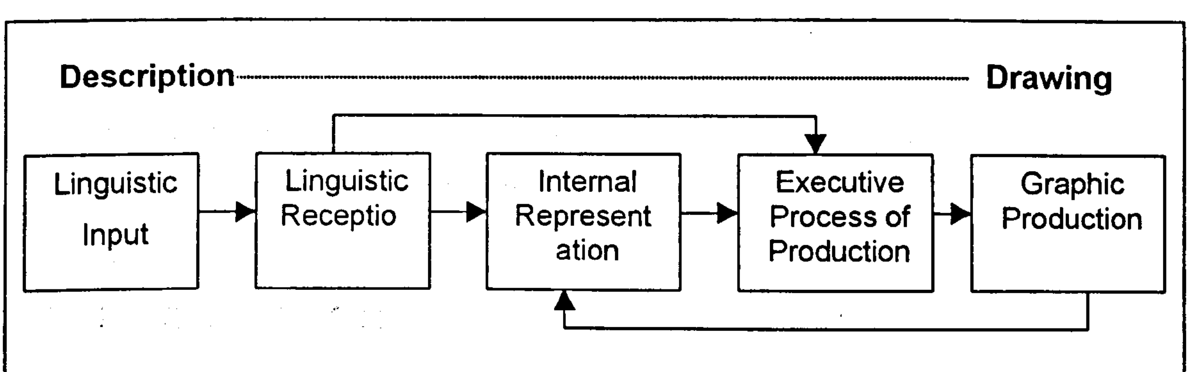


Figure 5.3: Hypothetical sequence of events from a verbal description to producing a drawing (from Drawings and Cognitive, by P. van Sommers p.113).

His study on how a drawing is constructed is revealed as the linear sequence of events (see, figure 5-3). Among these events, reception, internal representation and executive process may occur in mental space, and its processes are similar to the mental operations discussed above. Here, generating ideas can be likened with mental reception; mentally designing with internal representation; visualising mental image with executing a graphic production.

The upper arrow in figure 5-3 demonstrates that linguistic inputs can direct to performing drawings without internal cognitive representation; and the lower arrow represents that graphic execution can in turn affect the internal representation. In contrast with other drawing processes, in designing, the designer spends much more time in the feedbacks from the executive process to internal representation, that is, in modifying and refining the previous execution.

In addition, drawing is employed for manipulating many design elements and variables simultaneously and as a whole. The designer cannot keep a picture of an entire design situation in the mind and handle various objects at a time, so that he/she produces them on a working space (e.g., paper) in order to manipulate and store them. This is especially useful for architectural design in which numerous components are interacted in complex ways over the course of design.

Another important role of the drawings in designing, as Le Corbusier explained, is a function as 'memory':

> "as a practitioner of visual things... one sees with one's eyes, and one draws in order to take inside, into one's own history, the things that one sees.[73]"

That is, the objects in mental space fade away so promptly that the designer needs to depict the mental pictures by real objects with graphic symbols such as the sketch or model. Thus, drawing also serves as a tool for helping to manipulate images in a personal mental space in a particular way; the way that the designer finds it most helpful to think of the particular item of graphic information.

5.4 Conclusion

The aim of the theory of mental space is to understand the designer's mental process and to establish a theoretical foundation for the computation of designing, which is different from the problem-solving framework. I have employed the spatial analogy (mental space) of the designer's mind in order to inquire about the mental functions and operations that we cannot see as if it would be. In addition, I borrowed the theoretical background from cognitive psychology, in particular, *consciousness* *theories*, *surface theories* and other imagery theories. Thus, mental space shares some properties with the imagery systems such as visual working memory, visual buffer or mental models; however, it is identified that the designer's mental space maintains quite unique cognitive mechanisms and operations.

In computational terms, the designer's mind is seen as a system that has its own structures, operations and functions. From this, I distinguish three mechanisms – the memory system, the interface, and mental space. Even though they are interactive each other, each has its own functions and operations. I identify that whatever modes of internal representation were encoded and stored in memory, the interface of the mind plays a filtering role in presenting appropriate information. This is the function of the designer's attention or value system. Thus, the design process may depend more on the designer's perception and the mental performance in working memory than human cognition and the encoding-retrieving in long-term memory. From this observation, this thesis focuses on mental space in which the design ideas and images are created and developed rather than on the memory systems to which many CAAD researchers have given attention; and emphasises the function of imagery in the mental process rather than that of knowledge.

Parallelled with the mental structures, I describe three kind events of the mental operations in mental space – generating design ideas, designing in mental space, visualising mental features, which take place simultaneously and independently of the memory system. In doing so, I verify some main arguments in the thesis: that is, design involves the phenomenon of thinking/action that occurs in mental space; and designing (the mental process of designing) is a self-conscious activity. Finally, it is observed that during design, drawing provides the designer with the most powerful tool for keeping many things in operation at once, for self-communicating, as well as for exploring and analysing design.

In sum, Mental Space is a transitional realm that links between inner thinking and outward expression. Mental space serves as a medium that transfers external events or objects into the various symbols (internal representation) and re-transfers from internal representation into external process (external visualisation), and functions as a forum accommodating design thinking and design action at the same time and at the same place. The argument above carries some implications for developing the future computer systems for architectural design. In the next chapter, I will examine mental space as a design medium and in particular: (1) what the designer's mental space consists of; and (2) what affects these mental operations. These enquiries are necessary for meditating a mental space computer system.

Reference

[1] Bijl, A., *Computer Discipline and Design Practice: Shaping Our Picture*, Edinburgh University Press, Edinburgh, p.3, 1989.

[2] Young, R., 'Chapter one: Human nature and spatial nature', in *Mental Space*, Process press Ltd., London, 1994.

[3] Morris, P.E. and P.J. Hampson, *Imagery and Consciousness*, Academic Press, London, pp. 15-25, 1983.

[4] Ibid., p. 23.

[5] Young, R., *op.cit.*, 'Chapter one: Human nature and spatial nature'.

[6] Finke, R.A., *Principles of Mental Imagery*, The MIT Press, London, p.142, 1989.

[7] See, Johnson-Laird, P.N., *Mental Models*, Cambridge University Press, Cambridge, 1983.

[8] See, Kosslyn, S.M., *Image and Mind*, Harvard University Press, Cambridge, 1980.

[9] See, Young, R., *Mental Space*, Process press Ltd., London, 1994.

[10] Johnson-Laird, P.N., *Mental Models*, Cambridge University Press, Cambridge, pp. 1-22, 1983.

[11] Young, R., *op.cit.*,'Chapter one: Human nature and spatial nature'.

[12] Richardson, J.T.E., *Mental imagery and Human Memory*, The Macmillan Press Ltd., London, pp. 43-44, 1980.

[13] Pylyshyn, Z., 'The imagery debate: Analog media versus tacit knowledge', in *Imagery*, N.Block (ed.), The MIT Press, Cambridge, p153-158, 1981.

[14] Pinker and Kosslyn (1978) quoted by J.T.E. Richardson, *Mental Imagery and Human Memory*, *op.cit.*, p. 44.

[15] Finke, R.A., *Principles of Mental Imagery*, The MIT Press, London, pp.1-2, 1989.

[16] Jones, J.C., 'The state-of-the-art in design method', in *Design Method in Architecture*, G. Broadbent and A. Ward (eds.), Lund Huphries Publishers Limited, p. 194, 1969.

[17] Aoki, Y., 'An association model for a CAD system', in Artificial Intelligence in design '94, J. Gero and F. Sudweeks (eds.), Kluwer Academic Publishers, pp.219-236, 1994.

[18] Akin, Ö., *Psychology of Architectural Design*, Pion Limited, London, pp. 112-119, 1986.

[19] Marr, D., *Vision*, W.H. Freeman, San Francisco, 1982.

[20] Boulding, K.E., *The Image*, The University of Michigan Press (3rd Press), 1975.

[21] Beach, L.R. and T.R. Mitchell, 'Image theory: A behavioural theory of decision making in organisations', *Research in Organisational Behaviour*, Vol. 12, pp.1-41, 1990.

[22] Block, N., 'Mental pictures and cognitive science', *Philosophical Review '83*, pp. 499-542, 1983.

[23] Dennet, D.C., 'The nature of images and the introspective trap', in *Imagery*, N. Block (ed.), The MIT Press, Cambridge, p. 52, 1981.

[24] Block, N., 'Introduction: What is the issue', *Imagery*, *op.cit.*, p. 3.

[25] Paivio, A., 'Perceptual comparisons through the mind's eye, *Memory and Cognition*, Vol. 3, No. 6, p. 635, 1975.

[26] Paivio, A., 'A theoretical analysis of the role of imagery in learning and memory', in *The Function and Nature of Imagery*, P. Sheehan (ed.), Academic Press, New York, pp. 253-279, 1972.

[27] Paivio, A., *Imagery and Verbal Process*, Rinehart and Winston, New York, 1971, quoted by Morris and Hampson, *Imagery and Consciousness, op.cit.*, p.120.

[28] Bradshaw, J.L. and N.C. Nettleton, *Human Cerebral Asymmetry*, Prentice Hall, 1983.

[29] Bourne, L., R. Dominowski and E. Loftus, *Cognitive Processes*, Prentice-Hall, NJ, pp.70-73, 1979.

[30] Kosslyn, S.M., S. Pinker, G. Smith and S. Shwarz, 'On the demystification of mental imagery, in *Imagery, op.cit.*, pp. 131-150.

[31] Richardson, J., *Mental Imagery and Human Memory*, The Macmillan Press LTD, London, pp. 43-59, 1980

[32] Anderson, J.R., 'Arguments concerning representations for mental imagery, *Psychological Review*, 85, pp.249-277, 1978, quoted by J. Richardson, *Mental Imagery and Human Memory*, The Macmillan Press LTD, London, p. 43, 1980.

[33] Kosslyn, S.M., 'Scanning visual images: some structural implications', *Perception and Psychophysics*, 14, pp. 90-94, 1973.

[34] Morris, P.E. and P.J. Hampson, *Imagery and Consciousness*, Academic Press, London, p. 178, 1983

[35] Block, N., 'Mental pictures and cognitive science', *Philosophical Review 83*, pp. 499-542, 1983.

[36] Kosslyn, S.M., *Image and Mind*, Harvard University Press, p. 139, Cambridge, 1980.

[37] Farah, M.J., 'The neurological basis of mental imagery: a componential analysis', in *Visual Cognition*, S.Pinker (ed.), p. 250, 1986.

[38] Kosslyn, S.M., *Image and Mind, op.cit.*, pp. 139-147.

[39] Ibid., pp. 174-346.

[40] Kosslyn, S.M, *Image and Brain*, The MIT Press, Cambridge, pp. 53-77. 1994.

[41] Farah, M.J., *op.cit.*,pp. 248- 250.

[42] Dennet, D., 'The nature of images and the introspective trap', *op.cit.*, p. 52.

[43] Reed, S.K., *Cognition: Theory and Applications*, Brooks/Cole, Pacific Grove, p. 192, 1996.

[44] Le Corbusier, quoted by Pauly, D., 'The Chapel of Ronchamp', in *Drawings from the Le Corbusier Archive*, A. Tzonis (ed.), AD Editions Ltd., 1986.

[45] Winnicott, D.W., *Playing and Reality*, Tavistock Publications; reprinted Penguin, p. 118, 1971.

[46] Logie, R.H., 'Visuo-Spatial Short-term memory: visual working memory or visual buffer?, in *Imagery and Cognition*, C.Cornoldi and M.A.McDaniel (eds.), Springer-Verlag, New York, pp. 77-94, 1991.

[47] David, G and M. Olson, *Management Information System: Conceptual Foundations, Structure and Development*, McGraw-Hill (2nd ed.), p.200, 1985.

[48] Lera, S., 'At the point of decision', *Building*, May, pp. 47-48, 1982.

[49] Polanyi, M., 'Tacit Knowing: its bearing on some problems of philosophy', in *Review of Modern Physics*, Vol.34, pp. 601-616, 1962.

[50] Cross, N., 'Design method and scientific method', in *Design: Science: Method*, R. Jacques and J.A. Powell (eds.), Westbury House, pp.18-29, 1981.

[51] Cross, N., 'Design method and scientific method', *op.cit.*, pp. 18-29.

[52] Tulving, E, 'Episodic and semantic memory', in *Organisation of memory*, E. Tulving and W. Donaldson (eds.), Academic Press, pp. 385-386, New York, 1972.

[53] Anderson, J.R., 'Arguments concerning mental imagery', *Psychological Review*, No. 85, pp. 249-277, 1978.

[54] Reed, S.K., *Cognition: Theory and Applications* (4th ed.), *op.cit.*, p.192.

[55] Paivio, A., 'Perceptual comparisons through the mind's eye, *Memory and Cognition*, Vol. 3, No. 6, p. 635, 1975.

[56] Schwartz, R., 'Imagery – there's more to it than meets the eye', in *Imagery*, *op.cit.*, pp. 109-129.

[57] Reinschmidt, K.F. and G.A. Finn, 'Smarter computer-aided design', *IEEE Expert*, Vol.9, No.4, pp. 50-55, 1994.

[58] Richardson, J.T.E., 'Imagery and the brain', in *Imagery and Cognition*, C. Cornoldi and M. McDanniel (eds.), Springer-Verlag, New York, p. 3, 1990.

[59] Mole, A., *Information Theory and Esthetic Perception*', translated by J.E. Cohen, University of Illinois Press, Urbana, pp.124-169, 1966.

[60] Fodor, J.A., 'Imagistic representation, *Imagery*, N.Block (ed.), The MIT Press, Cambridge, p. 79, 1981.

[61] Hebb, D.O., *Organisation of Behaviour: A Neuropsychological theory*, Wiley, New York, 1949, quoted by V. Walsh and O'Mara, 'A selection on Attention', in *The Cognitive Neuropsychology of Attention*, Lawrence Erlbraum, Sussex, pp. 97-98, 1994.

[62] Weber, R., *On the Aesthetic of Architecture: A Psychological Approach to the Structure and the Order of Perceived Architectural Space*, Avebury, Aldershot, p. 52, 1995.

[63] Blackburn, S., *The Oxford Dictionary of Philosophy*, Oxford University Press, Oxford, 1996.

[64] Bahrick, H.P and B. Boucher, 'Retention of visual and verbal codes of the same stimuli', *Journal of Experimental Psychology*, 78, pp. 417-422, 1968.

[65] Eder, W.E., 'Engineering design—art, science and relationships', *Design Studies*, Vol. 16, No. 1, pp. 117- 127, 1995.

[66] Koestler, A, *The Act of Creation*, Macmillan, New York, pp. 229-230, 1994.

[67] Finke, R.A, *Creative imagery: Discoveries and Inventions in visualisation*, Erlbraum, Hillsdale, NJ, 1990.

[68] Ullman, S., 'Visual routine', *Cognition*, 18, pp.97-159, 1984.

[69] Denis, M., 'Imagery and thinking', in *Imagery and Cognition*, C. Cornoldi and M. McDaniel (eds.), Springer-Verlag, New York, pp. 103-131, 1991.

[70] Dennet, D., 'The nature of images and the introspective trap', *op.cit.*, p. 58.

[71] Schön D.A., *The Reflective Practitioner*, Harper Collins, USA, 1983.

[72] van Sommers, P., *Drawings and Cognition: Descriptive and Experimental Studies of Graphic Production Processes*, Cambridge University Press, Cambridge, p.106, 1984.

[73] Le Corbusier, *L'Atelier de la recherche patiente*, Paris, Vincent, p. 39, 1960, quoted by D. Pauly, 'The chapel of Ronchamp', in *Le Corbusier Archive*, A. Tzonis, AD Editions Ltd., London, 1986.

Chapter
6

Mental Space as Design Medium

Abstract: *This chapter examines the question about what designers represent in mental space and how they manipulate these components. In doing so, it will be discussed that a design consists of diverse representations – objects, relationships and events; these components have their own properties and functions for the design process and they can be furnished as elements in a design system. This chapter also contains the discussion on the roles of knowledge and imagery in mental space. It aims to establish a theory of mental space as a new theory for explaining designing, and further for computerising design.*

CHAPTER 6: MENTAL SPACE AS DESIGN MEDIUM

The architectural design process is often characterised as a series of evolving ideas, cycling between design and visualisation[1], in which design information transfers from design ideas to design product. However, the question about the nature of internal representation remains still unclear, that is, what is represented in mental space and what drives and influences the design mental process. It is necessary to make explicit a type of representation, the particular properties of the representation and the way of specifying information in the design domain in order to understanding the associated cognitive processes, especially, when we are thinking of programming a computer to mimic mental process

6.1 Representation in Mental Space

In cognitive psychology, representation is defined as *internal models* of individuals' environments and their actions in these environments, and they, as models, provide individuals with information on the world and serve as instruments for the regulation and planning of behaviour[2]. That is, representation links behaviour and the human mind governing his behaviour.

In computational terms, representation is seen as functional bases that describes a large number of facts (the objects) and the processes (the relationships) that cause those facts to change[3]. The represented information activates actions in a rational way. Therefore, it should be done ahead of making an intelligent system to determine on what to be represented and the ways to represent within computer system. The typical representational systems is knowledge-base system that can be easily stored in memory and manipulated by the inference mechanism for activating a reasonable behaviour toward goals. Thus, the fields of cognitive science and AI have focused on the representation of knowledge, such as acquisition, storage and manipulation of knowledge.

During designing, designers also represent mental outputs internally in their mental space and externally on the drawing board. As discussed in the chapter 5, the mental process in design is defined as the symbolic processing that represents information, including generating design ideas, designing mentally and visualising mental images. It is clearly a representational activity, in that it is involved in information-processing and expressed by a symbolic structure.

However, design representation can be distinguished to, and is different from the memory representation. Most significantly, the mode of representation in mental space is unique to the propositional mode in which that memory is generally stored and retrieved. That is, the designer is thinking visually[4] and is hence representing ideas in what is mainly a graphical mode[i]. Here, non-graphic representation seems to be imbued in graphic one of objects and events in mental space; and it make more difficult to articulate design representation verbally.

Moreover, not all of the mental outputs in mental space are derived from a pre-stored memory, and hence they are represented incidentally with incomplete forms and as a part of thought processes that extend over only finite (short) period of time. For these reasons, representing in mental space has very different function and structure from representation in a memory system. Below, I will define more precisely the characteristics of representation in mental space.

6.1.1 The Differences between the Representation in Mental Space and that in Memory System

There are two prevailing concepts in computing design processes – the concepts of a memory system and that of a problem space. Many computer systems have supposed that the human brain is an information-processing system like a computer; and a set of formalised memory or database can support every step of problem-solving activity. As a result, they have focused on the construction of storable representations in long-term memory and on the retrieval of information from it.

However, mental space is different from problem space. While problem space refers to a place where the solver searches for potential solutions by applying a finite

[i] Denis's experiment shows that the designer has the highest visual image latencies of 36 professions. See, *Image and Cognition*, Harvester, New York, p.105, 1991.

sequence of operations, mental space means a place that a design occurs in the mind. In problem space, design is regarded as a search process, and involves decision-making or knowledge-based activities. In the computational terms, while the problem space must be able to access declarative knowledge about facts in order to make inferences, mental space provides the designer with a space for exploring within an extension of his capacity for knowing and imagery.

Naturally, representation in a memory system is different from representation in mental space. While the former involves in storing perceptual experience and preparatory for recall or recognition, the latter involves in interpreting experience and is developed as mental images into a particular design. That is, even though the designer depicts the essential information from memory by perceptual process, he does not reproduce but rather reconstructs that information in mental space.

Thus, the initially represented design ideas (that represent 'the remembered experience' in the context of this thesis) are invented and recreated in mental space by the effects of imagery, independently of long-term memory. Thus, a mental space system would focus on refining and recreating information rather than on organizing information and retrieving from structured memory.

6.1.2 The role of the Designer's Value System

The objects or events in mental space constantly change their forms or properties and are always interpreted and reformed according to the designer's intended meaning. As discussed in section 5.3.4, human interface function as a filter that translates information between the outer world and inner experiences or between a new situation and a memorised event.

This filtering function occurs through the designer's value system. It affects the ways that the designer thinks, deals with the world and represents ideas. Each designer has the different value system; it makes the product of design different, even in the same project or designer. Lawson (1988) stated that design inevitably involves subjective value judgement: the designer's value system is itself affected by the exploration of objectives and what he finds to be possible and hence the design concepts constantly change during the design process[5]. Likewise, the values in design are highly context-dependent, subjective and changeable in the course of the compromises and trade-offs between the various possibilities and criteria.

Meanwhile, the designer's value derives from his own accumulated knowledge, experience or the shared image (in case of a group of people). It facilitates both the symbolic expression as true or false (descriptive value), and that as good or bad (relative value[ii]) in a certain course of action[6]. These values are involved indirectly in design representation but will be embodied in decision-making, judgement, and finally design production. Such value-laden characteristics in mental representation make it extremely difficult to computerise the designer's mental space.

As a result, it can be argued that representation in mental space is different from representation in memory system and is influenced by the designer's value system. It implies that a mental space design system is totally different from a memory-based design model or system. I will continue to examine how the designer represent and evolve his ideas in mental space in the light of a design computer system.

6.2 The Components of Design Representation

Denis (1991) defines representation as a human activity that consists in generating symbols[7]. In contrast with other professions, the designer is engaged, especially, in visual representation that creates objects derived from the interaction with the environment. During designing, architects can never recognise real space as a whole until the building is constructed, but only deal a space or form by symbols associated with the size of spaces, textile, colours, location of spaces, functions or its utility.

A symbol is something that stands for something else and it is a tool for representing a more complex idea into simplified image or knowledge. Such symbols permit the communication of enormously complicated, often abstract ideas with just a few lines, shapes or simple notes. For example, the rectangle, often in the early design stage, represents a room, the arrows refer to the movement of people or goods and bubble diagrams can imply the relationship between two spaces.

It is supposed, therefore, that any design is represented and refined in mental space, using with the symbols of picture-like or propositional format. These symbols do not

[ii] E. Bono names the value of design 'the relativity of value', and he asserts that design is the process of exploring values, reconciling values and creating new values; thus value is

only represent places or things, but they can also be an information that transfers a particular message or meaning. Thus, they are raw materials for representing design ideas and for performing the mental actions on the designer's mental space.

Based on these observations, the next question relates to what is represented in the architect's mental space, and how this representation is manipulated for designing. Before that, I posit three kinds of the abstracted constituents that represent or operate on information in mental space; that is, *objects*, *events*, and *relationships* as Figure 6-1.

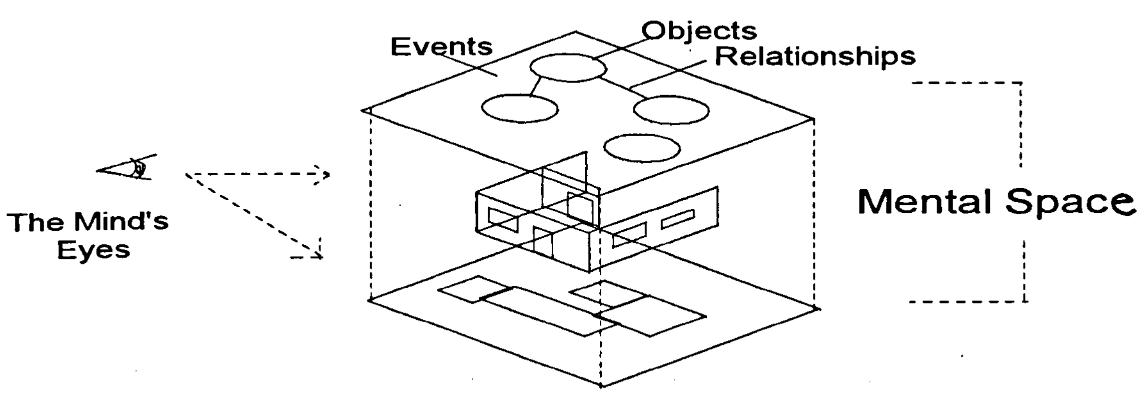


Figure 6-1: The concept of internal representation in mental space.

In mental space, **objects** symbolise the physical elements of design with its properties; **relationships** link objects or object and its properties; and **events** represent a design experience within a specific context. In other words, while the things that can be seen by the mind's eye are denoted as objects, the things that are invisible but can be conceived are represented as relationships, and both exist in temporal and spatial situation as an event. These constituents function as the significant resources not only to represent internal images and concepts, but also to visualise them on the drawing board. Finally, they can be analogised as the computational elements i.e., structured data, algorithms, graphic primitive elements, or operators.

at the heart of the design process.

6.2.1 Objects

Buildings are, physically, regarded as the combination of objects. The objects are represented in mental space with a concrete symbol; a shape or form, each of which depicts something in the designer's mind rather than what is actually seen. Each object has some extent and volume, and certain name and function, rather than being represented with geometric primitive symbols such as a line, a square or a circle. Thus, it is observed that the objects have their own specific attributes such as *name*, *location, forms*, and *movement*.

- **Names**

Most objects appearing in mental space have an identity in the sense that they possess names that serve as labels, for example, living room, and bedroom. The object name serves more than identity alone, since it represents common characteristics that it means and some general knowledge. For example, a living room implies its general function, its contents and so on. In addition, in a design cognitive process, name acts as a tag to retrieve from memory and to categorise various chunk of information into simple relationships.

- **Location**

Location is one of crucial geometric components in architectural design. Location appears in two-and three-dimensional form and its property includes distance, scale and orientation. Each value is determined by the utility and function of an object and their relationships between objects, after objects are located in X-Y-Z coordinate system. Such features are less clear and precise in the early design stage, but they become significant elements as the design processes, represented by conventional, mathematical symbols, especially in the detailed design stage.

- **Forms**

Architects usually deal objects in the 2 and 3 dimensional virtual space, and compose and develop them into a form of a room, a cluster, a building, a community and at last a city. The form is more evident in the whole in three-dimensional space, and it is represented along with material elements (texture, colour or light) and aesthetical elements (rhythm, harmony or symmetry). Thus, the ability to represent such properties may depend mainly on the designer's aesthetical experience and his imagery latencies.

The designer conceives the form of objects through various dimensions and viewpoints, looking them down from above, or observing them within the enclosed space. He/she travels mentally in the virtual space embodying a form, with analysing and testing their design suggestions and changing continuously the forms and layouts. Ultimately, design belongs to these mental processes, in order to establish the relationships between objects and furnish a form on those organised objects.

- **Movement**

Mental space can be committed also to the spatial analogy of moving through time. As the architect is sketching a plan, he takes part in moving, watching the changing relationship of objects in three-dimensaional space, and at the same time, places himself within the mental space looking into the future. The movement therefore involves the elapse of time. For example, the designer can walk though virtual space; touch the surface and material; feel the sense of place; and watch the movement of himself and objects in the virtual space. For this reason, the mental space employed in design is an active four-dimensional space rather than a three-dimensional one.

6.2.2 Relation Information

Relation is some kind of connection between two things, and is to combine the same attributes or functions to form category. The architect represents the semantic relation of objects, as well as the visual properties of objects. During designing, they represent amounts of relationships, such as spatial, hierarchic, functional, environmental, and so on. For examples of living room, living room must be adjacent to kitchen (spatial relation), elements-living room-cluster-buildings (spatial hierarchic relation), it serves for family's entertainment (functional relation), and it must be open to green (environmental relation).

Such relationships have accumulated as structured knowledge, information, or design resource that are meaningful in designing, design education or discipline. Thus, if the designer has more experience, he/she may have a more improved body of knowledge that contains various relations between objects and thus he can readily draw up solutions by using them.

In this way, relation is often a powerful vehicle in problem-solving, one that can direct a problem at a solution. It serves for retrieving images from schema or mental images in memory system and also for linking between objects and properties in mental space. Such a strong relation can be expressed as the logical form – rules, ordinances, numbers or 'if/then' propositions and its information are easily organised into the systematic relationships of cause-effect, supply-demand, or means-ends, and eventually, constructed smoothly into computer system. Thus, the compiled relation will be a fundamental component of the designer's knowledge base and will be a *schema* as separate module in design system.

However, many of relations represented in the designer's mental space seem to be loosely associated with each other. That is why there is no absolutely right answer for design decision-making. Moreover, the designer makes something, without ever knowing what is right. Accordingly, it is the more appropriate argument in design domain that there are no right or wrong answer (relation) in design, but only better or worse one[8].

In addition, the relations of design domain are, as Alexander and Poyner (1984) stated, those of *a question of value* as opposed to *a question of fact*, which can be only be judged by subjectively chosen criteria or values; there is therefore no basis for universal agreement[9]. Even though all design objects can be composed by any relation, many of them are so loosely connected and so entangled that it is difficult to specify some causal condition and effects. Inversely, such unrestricted relationship leaves the room in which the designer can present much creative ideas, in that the architect composes freely some objects; represents unexpected form and space; and travels in boundless mental space.

6.2.3 Event Information

Another form of representing in mental space is events. An event is, generally speaking, called an incident, an occurrence, or a particular happening in a situation. As discussed above, design objects are connected loosely to their functions, activities, utilities, or others. The relationships between objects are varied in time and space; and design is experienced at some place and in some time, that is, with its specific context.

Much of the information that architects deal with during design process can be classed as event-like. They are best described as 'in the case' or 'may be', not as 'if then' or 'should be'. It may be thought of as analogous to the narrative in literature as opposed to the description. Furthermore, such event information clings to personal experience and a specific context, and hence it cannot be learned by instruction but is achieved by the error and trial exercise.

Events are represented in mental space as a whole experience, as both the features of objects and their semantic relations. Those are available in the form of a repertoire of particular cases or precedent examples, in terms of which the designers are able to see the new situation. By perceiving a new situation as an element or elements of a repertoire and by doing in the new situation as they have done before, they can make use of their experience without exactly matching the same event. In addition, event information can lead the designer to a creative solution by mutation or analogical thinking.

Mutation is the deliberate action of changing features or attitudes of an object or concept in an unconventional manner. The purpose of mutation is to find new properties, functions and meaning of an old concept by looking a new situation from different perspectives[10]. Analogical reasoning has been known as the most prevailing strategies for architects to reach at new experience. It is useful to solve an unfamiliar problem from past perceptional experiences, without adequate or directly applicable information. Likewise, event information makes the designer readily access to existing design and it enriches and extend more the designer's mental space with representational variants on themes sensed within the meaning of the building.

In this section, I suggest three forms of representation in mental space: objects, relations and events. Simply speaking, objects represent mental images in a visual mode and their relationships represent design knowledge in a semantic mode. Meanwhile, events represent both objects and attributes within a specific context.

Among them, objects are the most important stuffs in mental space, which will be designed and developed into a design. In this process, information about events and relationships support the designer to generate and develop designs in each different way. While relation information serves for reasoning or decision-making, event serves for analogy, mutation or design reference. In design system, the former is encoded in memory system in the propositional mode, and the latter is stored as an episodic memory[iii], specific knowledge, or a precedent case that can be merged and adapted into new situation, without deep inspection of the memory system.

6.3 Knowledge in Mental Space

Before discussing the roles of knowledge in mental space, I intend to make clear the definition of knowledge. Here in the information-processing community, knowledge is manifold and differs with each purpose; that is, it is often exchanged synonymously and confusingly with such other words as data, facts, or information, but each of these words does not adequately stand in place of knowledge. Giarratano and Riley (1988) classified knowledge as a part of a hierarchy as noise; data; information; knowledge; metaknowledge:

> Data are items of potential interest; processed data are information that is of interest; knowledge represents very specialised information; and metaknowledge is knowledge about knowledge and expertise[11].

While information may be relevant to communicating and storing representations of knowledge[12], knowledge is concerned with thinking and interpreting the world, itself requiring the use of data and information. Patterson (1989) also states that knowledge combines relationships, correlation, dependencies, and the notion of gestalt with data and information[13].

However, the relationships among data, information and knowledge are, in fact, so intertwined that they cannot be easily classified. That is, they might often represent the same things; their meaning differs according to a particular context they are used in. In this thesis, knowledge is in general considered as a state of knowing and understanding a fact, and in computer terms, it refers to all the information chunks that we have represented in memory, including design facts, principles, or experiences.

[iii] Tulving proposed a division of memory into semantic and episodic memory. Semantic memory is defined as general knowledge about concepts that has been abstracted from individual experience. In contrast, episodic memories specify a definite time and place located in our own personal histories. See, Tulving, E., 'Episodic and semantic memory', in *Organisation of Memory*, E.Tulving and W.Donaldson (eds.), Academic Press, New York, p. 32, 1972.

6.3.1 Cognitive Process and Knowledge

Generally speaking, problem-solving activities are supposed as a series of conscious behaviours involving intelligence. Human intelligence involves a variety of capabilities, including reasoning, understanding, learning. These abilities are derived from knowledge stored in the solver's memory through inferring and generalising from acquaintance with facts. That is, humans can understand in a situation using knowledge that we have acquired in other specific situations.

It is not an easy task to understand the intertwined nature of human cognitive activities and to explain the role of knowledge in human thought and action. Greene, in *Memory, Thinking and Language* (1987), argues that knowledge plays the central role in interpreting the environment and that it influences on all human thinking, learning, speech and action as follows:

> "...It (knowledge) affects the way people perceive situations in the first place, which in turn activates previously learned procedures for dealing with the new situation. To complete the circle, the consequences of actions will themselves be stored in the form of new knowledge for deciding about future actions. This allows for the possibility of learning from new experiences, nothing procedures which have proved to be effective for dealing with a variety of situations. [14]"

Accordingly, knowledge has been regarded as the focus for explaining human thinking and activities, which can be explained with such psychological terms as cognition (the acquisition of knowledge) and cognitive process (representations and exploitation of knowledge). This cognitive approach has been applied to many areas as an identifiable theoretical standpoint for explaining human behaviour.

While cognitive psychology is the study of the mental operations that support human acquisition and use of knowledge[15], cognitive science and AI focus on cognitive systems—the design and testing of computer programs that carry out activities patterned after human thought and language. These fields share a background of information-processing theories, and most of them posit the priority of knowledge, in the belief that it plays a central role in interpreting and reacting in the world.

The concerns of cognitive science and AI are prior knowledge; in particular, how people use their prior knowledge to understand new or abstract ideas and to solve problems. Problem-solver organises his/her personal knowledge in rich, intricate chunks or schemata to construct a problem space. Schemata in memory theory are defined "an active organisation of past reactions, or of past experiences, which must always be supposed to be operating in any well-adapted organic response[16]". In AI, schemata has been employed as a unit of pre-packaged knowledge stored in memory, together with a number of related ideas such as 'frame' and 'script' or as modules in software. They contain information about the typical problem goals, constraints, and solution procedures for that kind of problem. Thus, a knowledge base, as a metaphor for human memory, means an organ that contains amounts of prior knowledge, which serve reasoning and solving problems. That is, if the problem solver – whether human or computer - finds a connection with prior knowledge, certain features of the problem may activate a schema for reasoning or solving the problem.

6.3.2 Knowledge in the Designer's Mental Space

The questions that the architect faces during design process are too comprehensive to specify and ranged from "which form is suitable for a function?" to "how wide should the corridor of the elementary school be according to regulations?" While the first kinds of questions are characterised as abstract, perception-like and visual mode, the second are as mathematical, memory-oriented, verbal mode. Encoding of different information will follow different representation modes and different actions. It can be supposed that the designer should use each different medium for different modes. In this thesis, the tool for handling the first kind of question is named imagery and that for the latter is knowledge, both of which are the main constituents in an operating mental process.

As discussed in the previous chapter, whatever the modes of representation are stored and encoded in memory system – pictorial or propositional, one can change functionally to the appropriate format of representation as the mental process requires. That is, the designer has already some faculties of how to select relevant information and actions to achieve perceived needs. Those faculties are acquired through practice and experience. Thus, knowledge can be operated in mental space, independently of memory system.

Knowledge in mental space is represented mainly in a verbal code and serves for linguistic processing. Represented knowledge is applicable to both wide range different circumstances and specific conditions. The former is called general knowledge and the latter specific knowledge[17]. While general schemata contain knowledge about the way the world is; domain-specific schemata embody the knowledge acquired during the years of professional work, and are built on top of the general schemata[18]. Knowledge in a design domain consists of a wide range of forms of knowledge from technical devices to the designer's know-how and experience. For examples, this knowledge would include the accumulated theoretical knowledge of design; the materials and techniques; legislative controls, codes of practice and other norms and standards; design methods and strategies about how to design and so on.

In computer terms, knowledge is usually distinguished between knowledge of fact and knowledge for action, since Anderson classified these two types as procedural and declarative memory[19]. While declarative knowledge refers to knowing that something is true or false or that a certain element within particular properties exists; procedural knowledge is referred to as knowing how to do something.

Procedural knowledge in a design domain is all knowledge of 'how-to's' that describes and predicts actions or plans of action. That is, knowledge that can be externalised as *if/then* verbal statement belongs to this category, and thus such knowledge is automatically triggered whenever *if* condition matches *then* action. As designers become more skilled in their tasks, they rely more on procedural and less on declarative knowledge[20]. From this, in computational AI, production (or reasoning) systems, or generic systems[21] usually focus on procedural knowledge in hope that the design process will be automated someday.

Meanwhile, declarative knowledge contains facts and design principles; for example, 'any living room must have at least one wall open to the outsider'. Such a schema labelled 'living room' may provide a lot of information that might help the designer to design a 'living room'. It is fulfilled by reference systems that contain amounts of declarative knowledge in various ways such as a database, a knowledge base or a case-base.

Carrara *et al.* (1994) proposed that design knowledge comprises three distinct, yet related, modalities: descriptive knowledge (what is being designed and how it performs); normative knowledge (why is it being designed); and operational knowledge (how is it being designed)[22]. Though the distinctions among these categories of knowledge are tautologically obvious, it is not immediately clear why they are needed and how they might be organised in a design system. The main reason for this is that their relationships are so interdependent that they perform a function together, rarely separately.

For example, the schema labelled a 'living room' serves not only to inform the designer its information, but it also prompts the need for a revision if the designer recognises that 'the living room is enclosed by others rooms'. That is, as a new problem is input, it initiates activating facts in declarative memory, and at the same time executes an action in procedural memory. In this way, design knowledge serves for design actions as well as for reasoning and solving problems.

6.3.3 The Roles of Knowledge in Mental Space

What roles does knowledge play in designing? There is a strong brief in cognitive science that knowledge gives substance to the problem and guides to solve it. In this context, designing can be seen as a task to find a physical form that will achieve the stated objectives. Alternatives and ideas that can potentially satisfy the objectives are proposed in mental space and they may be continually revised, or even abandoned.

That is, as a design proceeds, designer gains new insights; new aspects of a situation become apparent; and then new solutions or ideas are generated. The process of exploration and redefinition may continue until the designer has reached the limits of his understanding or imagery latencies. Thus, designing is often called searching or explorative process.

In this process, knowledge functions to extend the boundary of the designer's mental space where the designer explores and search for a solution. From this reasoning, Logan and Smithers (1993) say that the development of a design is constrained by the experience and knowledge the designer has at that time[23]. This demonstrates that knowledge and experience are valuable in understanding problem and making design. Next, I will examine the roles in knowledge in design problem solving and the implications for computation of design knowledge. In this thesis, I will focus simply on two functions: reference roles and the role of solving problem.

Design Knowledge as References

Information theories have defined information as "data that has been processed into a form that is meaningful to the recipient and is of real or perceived value in current or prospective actions or decisions[24]". When dealing with a new problem or confronting a judgement in a design process, the designer requires information that can provide design references for solving blocked problems. From the observation of the designers at work, Levin (1984) identified that the designer dealing with the interaction between man and the built environment needs a much greater body of knowledge of in order to arrive at appropriate decisions, than that associated with other disciplines[25].

In an open-ended design process, there are many alternatives that imply not what ought to be, but what may be possible. Even possible decisions are continuously evaluated, modified, and then chosen till the designer feels satisfies. Here, under uncertain or less objective circumstances, knowledge that is based on scientific facts plays powerful roles in aiding the designer to validate their decisions.

Parallelled with personal knowledge and experience, Burnette (1979) emphasises the role of externally available information as follows:

> "The essence of professionalism is judgement. What distinguishes the judgement of a professional from that of a lay person is the professional's access to relevant information, his accumulated knowledge and his ability to apply this information and knowledge appropriately. Traditionally, these capacities have been the result of the interests, education and experiences of the individual architect.[26]"

It is a common tendency in 'the information age' that professional judgement is increasingly dependent on direct access to information and to the appropriate techniques for applying it. Today the complexity of design and building problems requires more information, knowledge and experience than a single individual can possess, and thus the designer's environment is filled with excessive information. Design seems to be knowledge-rich activity, as Lawson (1994) asserts, in that design requires us to have considerable amounts of knowledge beyond that which is stated in the problem description[27].

The real problem is, therefore, how exploit information, timely and in appropriate forms, at each stage of the process; how to draw out a potential solution from information. In this context, the quality of solution depends on the solver's abilities to store, retrieve, and manage the related information. Information is converted in the designer's mind into design knowledge, some of which can be the means of solving a problem or some may ultimately become solutions[28]. Through these processes, design knowledge or information can be used as a reference tool to develop a design and as a resource to make better decisions.

These notions can be the starting points for design information systems or design reference systems that supplement the limitations of human abilities in storing, retrieving and managing information or knowledge. That is, declarative information can be formalised as pre-structured knowledge in a computer and then this knowledge can support every step of designing in significant ways through cognitive processes. The system includes database systems, decision support systems, and communication systems, which can provide newly updated and correct information to an agent's knowledge base or database.

Knowledge for Solving Design Problems

It is self-evident that knowledge plays a crucial role in a cognitive process such as problem-solving or reasoning. Humans can reason or understand (in) new situation by using knowledge that we have already acquired. Simon (1973) argues that any problem – whether ill-structured or well-structured – has a potentially relevant knowledge base: there may be nothing other than the size of the knowledge base to distinguish between the characteristics of problems[29]. The design problem is a typical ill-structured problem and requires an exhaustive bank of pre-structured knowledge –whether in a designer's memory or in a computer's knowledge-base.

Hillier *et al.* (1984) emphasise on the role of the designer's pre-structured knowledge. According to them, design conjectures and ideas do not, on the whole, arise out of the external information such as client's demands, norms and technological means, but come from largely the pre-existing knowledge of the instrumental sets, solution types and informal codes.[30]

In this context, knowledge is the results of interpretation and it depends on the sum of previous experience and on situatedness[31]. Pre-existing cognitive schemata guide the designer to structure the problem in terms in which he can solve it and to find a satisfactory solution. Then they trigger design actions or inform decisions taken in pursuit of design goals.

Information movements in systems such as generating, learning, or transforming information are performed on the basis of fully articulated knowledge. It is one of the goals of design studies to explicate design norms, strategies, technique or creative methods that the designer uses into a form of knowledge. Such design methods could be employed directly in designing in order to generate candidates and design solutions, and to predict and evaluate their expected performance. In this context, design knowledge is a 'transportable substance[32]' that can be perfectly formulated, recorded, and made ready for use in terms of the scientific method, and that can guide future design action. Moreover, in terms of the computer, such problem-solving systems aims to automate the design process with the hope that design knowledge can be externalised and thereby improve the quality of design decision-making.

However, any design – especially architectural design – is entangled with large quantities of elements, rules and facts, and relationships to be taken account, and thus it may require a very large, perhaps infinite mass of knowledge sets to tackle real design. Moreover, most of the knowledge presented by the designer - during design or after design - is not explicit; only a relatively small part is amenable to verbal description.

From this observation, the reason that the designer's work is inexplicable is, as Daley (1982) asserts, not for some romantic and mystical reason, but simply because these processes lie outside the bounds of verbal discourse: that is, they are literally indescribable in linguistic terms[33]. A major obstacle is to formalise and acquire design knowledge, then, to translate it into computer program in a design system. As a result, the assumption that a set of 'complete' knowledge can solve design problems has not been accepted in the computed design field. And, maybe, this is a Holy Grail.

Architects exploit tacit knowledge in design process, such as analogy from precedent designs, intuitive inspirations, or accumulated personal experience. Such knowledge cannot be easily rendered explicit, despite holding significant roles in design cognitive process. These design elements that cannot be formalised as verbal symbol systems will be accounted for through the ideas of *imagery* in next section.

6.4 Imagery in Mental Space

As seen in the previous chapter, image generations in mental space begin by retrieving information about the appearance of objects or the properties of events from a memory system. This information is stored randomly in the general form of pictures, propositions or both. When encoded a new information, a retrieved or generated mental image is then constructed as a concrete shape within mental space, and it develops finally to a design through a mental visualising process and drawing action. Here, it is hypothesized that imagery functions as another mechanism of the designer's cognitive process that can be distinguished from knowledge.

The distinct feature of imagery is that it can be conducted independently of memory. Psychological experiments, which show that totally, congenitally blind subjects can also experience visual imagery[34], demonstrates that imaginal representations can be activated in working memory in the absence of external visual long-term memory representations.

Accordingly, I suggested in the previous chapter that imagery is different from the mental image. While image is a visual representation in memory or the short-term retention of visual information in mental space, (mental) imagery is instrumental in retrieving information about the physical properties of objects, or about physical relationships among objects, that was not explicitly encoded at any previous time[35]. Furthermore, imagery contributes to transfer information in mental space and to develop a design drawing. Imagery is therefore defined in this thesis as *the faculties or a design strategy that can lead mental images to produce or make something*.

That is, mental imagery is not simply a phenomenal experience, but a medium in which information about the visual appearance of physical objects can be depicted and manipulated in a mental space. Therefore, representing visual images in memory systems and mental space is only a low-level function of imagery, and more significantly, imagery can serve for aiding conscious thinking and problem solving[36], and creative thinking.

6.4.1 Imagery in Design Problem-Solving

It is argued by the anti-imagery researchers that imagery is an irrelevant byplay of more abstract cognitive processes and, thus, has a purely "epiphenomenal[37]" status in cognition. Yet, increasing experimental evidence strongly suggest that imagery is of functional importance in information-processing and there are many types of problems for which imagery can provide short cuts to the final solution, such as through a visual analogue without having to carry out an extensive logical analysis[38]. The evidence that images play a role in the cognitive process can be identified even in the everyday life, such as, helping to give directions or to picture old friends. From this respect, imagery emerges once again as a topic of research in cognitive psychology[39], with a hope that it would remove some of the mystery about how the human mind works.

A variety of evidence suggests that visual images are important to our ability to perform many spatial reasoning tasks. For examples, Kosslyn (1978) and his associates' study of *image scanning* demonstrated that visual images preserve the spatial relations among the objects of a scene.[40] The results suggest that we can mentally scan visual images in the same way that we can scan pictures. Another experiment, the result of Shepard and Metzler's *mental rotation* study (1985) showed that when we are comparing two patterns that are in different orientations, a visual image makes it possible to rotate one of them mentally until the two pattern have the same orientation [41]. Besides of the spatial tasks, Kaufmann (1990) argued the case for imagery effects on the general reasoning processes – deduction and induction. Deductive operations are translated into image comparisons, and then certainty of judgement may be reached, meanwhile, inductive operations are the anticipations of image, where a future state of affairs may be imagined on the basis of a previous sequence of events.[42]

More precisely, Denis (1991) identifies that there are three functional properties of images relevant to problem solving: *the structural similarity, the integrative potential,* and *the transformations.* That is, the advantages of images in problem solving are that they have a structural organisation similar to that of perception and they maintain a large number of informational units together as a unified whole in a flexible and swift manner[43]. Likewise, cognitive psychology researches illustrates how images can be used to improve performance on many cognitive tasks, including processing spatial relations between different parts of a object, reasoning through image comparison and anticipation and problem-solving in some specific domains.

During designing, architects deal with visual images of objects or events in mental space such as materials, rooms, or building, and its semantic representation. They reconstruct or synthesize these components into a design through the function of imagery. In this process, imagery retrieves information from memory and through the perceptual process, imagery represents its objects and events in mental space and thereby produces a design. Making a design in mental space is the principal role of imagery in design, and involves judging spatial relationships, synthesizing objects, creating new form and so on.

Among them, the strategy of drawing or modelling mentally – namely mental simulation - may be most frequently employed by the designer because it contributes to efficient design problem solving by simulating physical events in boundless space. Imagine a design task: architects may stand in the middle of his mental space, with exploring a given function and a conceived form, comparing some alternatives or feeling materials of building.

At the same time, they hold and maintain these mental features on a paper or hopefully computer screen. This mental simulation provides insights that might have been overlooked if the designer only considered formal or analytical methods in solving problem and it also helps save considerable efforts in wasted trial and error[44]. In additions, mental simulation provides forum where amounts information can be simultaneously represented and maintained, and often generates unexpected ideas – creative thinking.

Likewise, imagery can be used in reasoning or problem-solving, in which mental synthesis and mental modelling are the useful functions for design problem solving. More significantly, the relevance of imagery is linked the ill-structured problem characterised by novelty, complexity, and ambiguity[45], and a visual information processing like design problems.

6.4.2 Creative Thinking and Imagery

Design and creativity go hand in hand; especially in the early stage of designing. From the romantic view, creativity is seen to be inherent in the mind itself, the artistic talent given at birth. Jones (1969) named the design activities performed from intuition as the '*black box*' and defined creativity as the mysterious *leap of insight*[46]. Similarly, Archer (1984) also indicated that the creative leap from pondering the question to finding a solution is *the real crux of the act of designing*[47]. Meanwhile, the mathematician Hadamard (1945) regarded it as the unconscious realm, including incubation and illumination stages[48].

However, there is suggested another way of thinking about creativity, that is, thinking of creativity as centrally manifested in problem-solving activities. These attempts have been pursued by cognitive psychologists and AI researchers[49] who have been influenced effected by modern information theories. They suggest that creativity may not be all that mysterious and that it may simply be good problem solving[50]. From this, they establish the general hypotheses that creativity is manifestly a cognitive process, which is not significantly different in nature from everyday thinking and reasoning and is also involved in a mental processing of symbolic structure.

These observations, regardless of whether computers can really be creative, have led design and AI researches to focus on a computational model for the non-rountine or creative design[51]. Reed (1996) identifies trends in the research for a problem-solving paradigm in each decade: The 1970s focused on work on how people use general heuristics to search problem spaces; the 1980s on how acquisition of domain-specific knowledge is required to become an expert; and the 1990s on the study of creativity by contributing new insights about imagery[52].

In contrast with traditional problem-solving domains, imagery theories have provided a new resource to explain creativity. It is generally accepted that imagery might play an important role in creative thinking, invention or scientific discovery, and could be used to guide the creation in the absence of explicit instructions for how to do. In short, as Anderson (1989) argues, people draw on imagery to create something; creativity is the execution or expression of imagery, the communication of inner imagery to others[53].

In this way, imagery is used not for the questions of simply correct or wrong but that of novel and useful. In the design process, it may allow the designer to explore creative combinations of objects, to suggest all possible events, or to discover meaningful objects, shapes or patterns. Imagery does not occur in a dream state but in creative thinking, to be somehow different or to be original. Shepard (1978) argues that the following characteristics of imagery make it a powerful tool as part of processes in creative thinking.

> (1) imagery is less constrained by tradition than language; (2) the richness of imagery makes it possible to note significant details and relationships that are not adequately contained in purely verbal representations; (3) the spatial character of images makes them directly accessible to potent competencies for spatial intuition and manipulation; and (4) vivid images may constitute more effective substitutes for corresponding external objects and events than it is possible to achiever with a purely verbal representation[54].

Such properties of imagery as richness, vividness, and fluidity, lead the designer to think in highly novel and serendipitous ways, to see a hidden part and relation in events, and hence to reach a creative solution. Thus, creative thinking means creative exploration in mental space. In such exploration, imagery can be used as an incentive that generates or develops the designer's intuition and imagination to achieve a creative solution. These observations suggest that the appropriate role of computer in the design domain be for providing an environment to motivate and enhance the designer's potential for creativity rather than to solve design problems.

6.4.3 Interaction between Intuition and Intellect

The last suggestion in this thesis is that imagery can trigger and activate the mental interaction between intuition and intellect to attempt to solve a design problem. Dictionary defines intuition as immediate apprehension by the mind without reasoning[55]. As discussed in the previous section, intuition plays a major role in any creative activity and thus the term 'intuitive creativity' is often coined. Intuition derives from the designer's insights, emotions, or experiences. Arnheim (1986) defines intuition as the ability to apprehend directly the effect of an interaction taking place in a field, and so regards it as one of particular properties of perception[56]. It is accounted for thus as a gift bestowed by the gods or by heredity; mysterious and very personal.

In a problem-solving process, intuition is regarded as a cognitive process, even though it is not based on but influenced by prior knowledge, insight or shared culture. That is, intuition is not mysterious but is a phenomenon of perceptual representations from memory; the main reason that it is difficult to recognise and articulate its mental processes may be that intuition appears incidentally and fades away immediately in mental space.

Designing often depends on creative intuition, imagination or fancy. It also requires the relevant knowledge and techniques to evaluate or validate his ideas. Obviously, both intellect and intuition are needed in design, and the control and combination of them are one of the designer's most important skills[57]. There is little doubt that intuition and intellect play a mutual supplementary role in generating design ideas and developing them. Arnheim (1986) identifies this co-operation as follows:

> "Intuition is privileged to perceive the overall structure of configurations. Intellectual analysis serves to abstract the character of entities and events from individual contexts and defines them 'as such'. Intuition and intellect do not operate separately but in almost every case require each other's co-operation.[58]"

Both abilities of intuition and intellect are equally valuable and equally indispensable for human thinking. Thus, it can be supposed that the good designer not only generates more easily valuable possibilities in imagination and appropriate knowledge from his/her memory but also harmonises them with particular skill

If intellect and intuition represent ends of a continuum rather than distinct types, a question emerges: what fills the gap between them. It is suggested in this thesis that imagery may hold this connecting role. Even though the psychological evidence for this assertion must be further tested, practically the designer seems to use imagery in order to integrate knowing something and having an instant insight.

When a design problem is perceived, imagery represents tentative images in mental space by intuition and intellect in mental space, and develops them by activating mental interaction between them. The flexible property of imagery makes this interaction readily available to aid the production of a creative design. For example, at any stage of cognitive development, knowing the relevant event helps generate intuitive imagination and, in turn, rich imagination helps combine knowing in manifold, unusual ways, thus helping to extend the boundaries of each other. From such an observation, I suggest that imagery can be considered an agency that stands at the midpoint between intuition and intellect, which aids creative thinking and conscious problem solving.

6.5 Discussion

In chapter 5, I examined the structure of mental space and explained about what happens in this virtual space. In this chapter, I accounted for the functions of mental space as a medium to reach a design solution, by articulating its components and the roles of knowledge and imagery. In doing so, I identified that a design consists of diverse representations consisting of objects, relations and events; these components have their own properties and function within the design process; and through the designer's knowledge and imagery they are operated on in mental space.

Design knowledge serves different roles driving the design process. In the process, certain types of design knowledge may help the architect to generate a solution directly, some may exist to transform data into useful information, and some may aid the validation of his/her conjecture. Here, I refer the former two roles to knowledge as design reference and the last to knowledge for solving design problem.

In addition to knowledge, imagery is also a basic form of cognition, and plays a central role in many human activities, ranging from navigation to creative problem-solving[59]. In problem-solving processes, the use of imagery can be considered as one of strategies which optimise the conditions for a representation. Thus, imagery-based strategies enhance the designer's problem-solving and creativity. Even though the evidence is still incomplete, it is suggested that imagery can function for filling the gap between intuition and intellect, which may be the most important quality to harmonise knowing and imagination.

Knowledge and imagery do not work alone. In a design activity, they are interdependent and this observation forms a basis for mental space theory. In here, I attempt to integrate two concepts of knowledge and imagery in mental space through the metaphor of the designer mind. While the studies of knowledge is relatively easy to articulate and well-established, imagery theories are still relatively contentious.

Even so, I suggest that this theory can be applied as a theoretical foundation not only for computation of designing but also to general design studies; that is, it could provide a theoretical background for explaining the subjectivity and variability of design. It may also provide a route towards better-computed design. Basing on this mental space theory, next chapter will examine the feasibility of mental space as design computational metaphor.

Reference

[1] Simon, H.A., 'The structure of ill-structured problem', *Artificial Intelligence*, 4, pp. 181-200, 1973.

[2] Denis, M., *Image and Cognition*, Harvester Wheatsheaf, New York, p. 13, 1991.

[3] Bench-Capon T.J.M., *Knowledge Representation: An Approach to Architectural Intelligence*, Academic Press Limited, London, p. 11, 1990.

[4] Trovey, M., 'Thinking styles and modelling system', in *Design Studies*, Vol.7, No.1, pp.20-30, 1986.

[5]Lawson, B., *How Designers Think*, Butterworth Architecture, London, pp. 89-91, 1988.

[6] de Bono, E., *Parallel Thinking*, Penguin Books, London, pp. 187-194, 1994.

[7] Denis, M., 'Preface', in *Image and Cognition*, Harvester, New York, 1991.

[8] Wade, J.W., *Architecture, Problems, and Purposes: Architectural Design as a Basic Problem-Solving Process*, John Wiley & Sons, New York, p. 21, 1977.

[9] Alexander, C. and B. Poyner, 'The atoms of environmental structure', in *Developments in Design Methodology*, N. Cross (ed.), Wiley, Chichester, pp.123-133, 1984.

[10] Maher, M.L., and F. Zhao, 'Dynamic associations for creative Engineering design', in *Modelling Creativity and Knowledge-Based Creative Design*, J.S. Gero and M.L. Maher (eds.), Lawrence Erlbaum Associates, NJ, pp. 329-351, 1993.

[11] Giarratano, J. and G. Riley, *Expert System*, PWS-KENT Publishing Company, Boston, pp. 64-66, 1989.

[12] Stefik, M., *Introduction to Knowledge Systems*, Morgan Kaufmann Publishers, Inc., San Francisco, p. 394, 1993.

[13] Patterson, D.W., *Introduction to Artificial Intelligence and Expert Systems*, Prentice-Hall International, Inc., p. 11, 1989.

[14] Greence, J., *Memory, thinking and Language: Topics of Cognitive Psychology*, Methuen, London, p. 14, 1987.

[15] Reed, S.K., *Cognition: Theory and Applications (4th ed.)*, Brooks/Cole Publishing Company, Pacific Grove, p. 4, 1996.

[16] Bartlett, F.C., *Remembering*, London, Cambridge University Press, 1932, quoted by David F. Marks, 'On the relationship between imagery, body and mind', in *Imagery*, Routledge, London, p. 8, 1990.

[17] Stefik, M, *op. cit.*, p. 299.

[18] Goel, V. and P. Pirolli, 'Design within information-processing theory: the design problem space, *AI Magazine*, pp. 25-26, spring 1989.

[19] Anderson, J.R., *The Architecture of Cognition*, Harvard University Press Cambridge, 1983.

[20] Akin, Ö., *Psychology of Architectural Design*, Pion Limited, London, p. 34, 1986.

[21] Achten, H., *Generic Representations*, Bouwkunde, Eindhoven, 1997.

[22] Carrara, G., Y.E. Kalay and G. Novembri, 'Knowledge-based computational support for architectural design, *Automation in Construction,* 3, pp.165-166, 1994.

[23] Logan, B. and T. Smithers, 'Creativity and design as exploration', in *Modelling Creativity and Knowledge-Based Creative Design*, J.S. Gero and M.L. Maher (eds.), Lawrence Brlbraum Associate, New Jersey, pp. 139-175, 1993.

[24] David, G. and M. Olson, *Management Information System: Conceptual Foundations, Structure and Development*, McGraw-Hill (2nd ed.), p. 200, 1985.

[25] Levin, P.H., 'Decision-making in urban design', in *Developments in Design Methodology*, N. Cross (ed.), John Wiley & Sons, Chichester, pp. 197- 122, 1984.

[26] Burnett, C., 'The architects access to information: constraints on the architect's capacity to seek, obtain, translate and apply information', in *National Bureau of Standards GCR*, pp. 78-153, 1979.

[27] Lawson, B., *Design in Mind, op. cit.*, p. 6.

[28] Willem, R.A., 'On knowing design', *Design Studies*, Vol.9, No.4, p. 224, 1988.

[29] Simon, H.A., 'The structure of ill-structured problems', *Artificial Intelligence*, 4, pp. 181-200, 1973.

[30] Hillier, B., J. Musgrove, and P. O'Sullivan, 'Knowledge and Design', in *Developments in Design Methodology*, N. Cross (ed.), John Wiley & Sons, Chichester, pp.245-263, 1984.

[31] Winograde, T. and F. Flores, *Understanding Computers and Cognition*, Addison-Wesley Publishing Company, Reading, pp. 70-79, 1987.

[32] Stefik, M., *Knowledge Systems, op. cit.*, p. 295.

[33] Daley, J., 'Design creativity and the understanding of objects', in *Design Studies,* Vol.3, No.3, pp. 133-137, 1982.

[34] Ernest, C.H., 'Imagery and memory in the blind: A review', in *Imagery and related mnemonic processes: Theories, individual differences, and applications*, M.A. McDaniel and M. Pressley (eds.), Springer-Verlag, New York, pp. 218-238, 1987.

[35] Pinker, S., 'Visual cognition: Introduction', in *Visual Cognition*, S. Pinker (ed.). The MIT Press, Cambridge, pp. 1-63, 1986.

[36] Morris, P.E. and P.J. Hampson, *Imagery and Consciousness*, Academic Press, London, p. 4, 1983.

[37] Pylyshyn, Z.W., 'What the mind's eye tells the mind's brain: A critique of mental imagery, *Psychological Bulletin*, No.80, pp 1-24, 1973.

[38] See, Beveridge, M. and E. Pakins, 'Visual representation in analogue problem solving, *Memory and Cognition*, No.15, pp. 115-147, 1987.

[39] Block, N., 'Introduction: What is the issue?', in *Imagery*, N. Block (ed.), The MIT Press, Cambridge, p. 1, 1981.

[40] Kossyln, T.M., T.M. Ball and B.J. Reiser, 'Visual images preserve metric spatial information evidence from studies of image scanning', *Journal of Experimental Psychology*, 4, pp. 47-60, 1978.

[41] Shepard, R.N and J. Metzler, 'Upward direction, mental rotation, and discrimation of left and right turn in maps', in *Visual Cognition, op. cit.*, pp. 161-193.

[42] Kaufmann, G., 'Imagery effects on problem solving', in *Imagery: Current Developments*, Routledge, London, p.173, 1990.

[43] Denis, M., *Image & Cognition*, Harvester, New York, pp.155-168, 1991.

[44] Finke, R.A., *Principles of Mental Imagery*, The MIT Press, Cambridge, pp. 141-155, 1989.

[45] Kaufmann, G., 'Imagery effects on problem solving', in *Imagery: Current Developments, op. cit.*, pp. 172-173.

[46] Jones, J.C., 'The state-of-the-art in design method', in *Design method in Architecture,* G. Broadbent and A. Ward (eds.), Lund Huphries Publishers Limited, p. 194, 1969.

[47] Archer, L.B., 'Systematic method for designers', in *Development in design methodology, op.cit.,* pp. 57-82.

[48] Hardmard, J., *Psychology of Invention in the Mathematical Field*, Princeton University Press, Princeton, N.J., 1945.

[49] See, Dasgupta, S. *Creativity in Invention and Design*, Cambridge University Press, 1994.

[50] Reed, S.K., *Cognition: Theory and Applications, op. cit.*, pp.385-411.

[51] See, Gero, J.S. and M.L. Maher (eds.), *Creativity and Knowledge-Based Creative Design*, Lawrence Brlbaum Associates, NJ, 1993.

[52] Reed, S.K., *Cognition: Theory and Applications, op. cit*, p.408.

[53] Anderson, R.L., *Art in Small-Scale Societies*, Prentice-Hall, Englewood Cliffs, pp.131-132, 1989.

[54] Shepard, R.N., 'The mental image', in *American Psychologist*, No. 33, pp.125-127, 1978.

[55] The Concise Oxford Dictionary, 9th ed., D. Thompson (ed.), Clarendon Press, Oxford, 1995.

[56] Arnheim, R., *New Essays on the Psychology of Art*, University of California Press, Berkeley, p. 13,1986.

[57] Lawson, B., *How designers think, op. cit.*, p. 101.

[58] Arnheim, R., *New Essays on the Psychology of Art, op. cit.*, p. 29.

[59] Kosslyn, S.M., *Image and Brain: The Resolution of the Imagery Debate,* The MIT Press, Cambridge, p.1, 1994.

Chapter
7

Mental Space as Design Computational Metaphor

Abstract: *This chapter describes a mental space computational model (MSCM) based on th theory of mental space. This theory provides a new understanding of the potential roles of computer for architectural design – visualising design tools and reference tools. Here, I examine the feasibility of mental space as computational metaphor and consider its potential as the basis for a design system. I argue on the computation o mental space and some case-studies on the existing CAAD systems. This chapter also includes the proposals for a new approach and a discussion of future implications of mental space theory for architectural design system.*

CHAPTER 7: MENTAL SPACE AS DESIGN COMPUTATIONAL METAPHOR

Since the 1950s, the guiding metaphor for developing theories for cognitive systems has been the brain as a computer, in that the crucial feature of the brain and computer is that both are information-processing systems[1]. Both internally store information from the environment in memory, and this stored information serves for the basis for human behaviour or the system operations. In each case, this information must take some form of representation. Thus, the notion of representation has had an enormous influence on building the cognitive models, and in fact, researchers in the CAAD domain have carried out various investigations of the mental process in terms of the representation in a database or a memory system.

Throughout the previous chapters, however, I observed that most of memory-based systems have proved not to be amenable to the architectural design process. From this, I have suggested that designing is a phenomenon of design *thinking/action,* and is different from a general design problem solving process. I have also suggested *mental space* as an analog of how the architect processes information and have tried to identify its structures and functions in order to give insights into what a design system should be. In this chapter, I will examine whether mental space could be a feasible mental model for the computation of architectural design and will draw its potentials as a design system that can be distinguished from the predominant memory-metaphor system. To do so, first of all, I will argue why such a new design computational model is needed.

7.1 The Needs of A New Theoretical Framework for CAAD

Many applications in the design domain have been developed and marketed for drafting or analysing a design problem, but no system, so far, fully supports the designer in the earlier design stage where a real design occurs in - design *thinking/action* (see, table 7-1). There are many reasons why designing cannot be easily simulated in a computer program. Most of all, both designing and computation have different languages; while design is communicated graphically, computers (currently) do so linguistically; while design generates values, computers generate the anticipated results.

Table 7-1: The application of computers in design three stages

	Problem stage	Design stage	Detail drawing stage
Applications	Information systems, Knowledge systems, Analysis and Evaluation programs.	?	Graphic tools, Presentation software.

These gaps do (or will) not narrow with today computer techniques or capacities. This, then, is a fundamental problem of the conventional paradigm for the computation of architectural design; that is, the computer must accommodate the distinct nature, language and activity of design. This involves more than a problem-solving process. In this regard, it is more important to establish a new theoretical model for what the computer can do for design than computerising design with increasingly advanced techniques.

There exists an obvious shift in the viewpoint of the computer for design, from the *computability*[i] *of design* to the *usefulness of the computer* for design. CAAD research in the 1980s focused mainly on computerising design activities or its process, and hence many systems tried to adjust the design problems to limited computer technologies or related theories. This direction was dictated by what computers were capable of (or expected to be capable of) at that time. Following this route, designing has been interpreted in terms unfamiliar to the architect, like a search process, decision-making, or knowledge-based activities, which were parts of the theoretical patrimony adapted by most neighbouring computer-related fields. This meant that computation has been the goal and design the means; the computer a subject and the designer an object.

[i] The word 'computability' is borrowed from the title of book *Computatbility of Design*, Y.E.Kalay (ed.), John Wiley & Son, New York, 1987.

Although it is inevitable that CAAD depends on the development of other science and technologies, design systems should be devised on the basis of the designer's actually thinking and acting, not by merely adapting the technology of neighbour sciences. This demonstrates the necessity of a designer-centred approach to understand how a design system should be used for the design process. However, the more deeply we investigate the designer's behaviour, we recognise, the more difficult the computability of design is. Even though cognitive psychology and science have provided some insight and clues in examining design, it is not enough to explain and computerise the complexity and idiosyncratic characteristics of design.

If we give up on the idea of computerising the design problem solving process as a *whole, then, all that* left is the usefulness of computers as a prescribed design tool. Some theorists in AI or design domain have already *developed such arguments as* follows: By bringing Heideggerian philosophy to the fore, Coyne and Snodgrass (1993) have widened the scope of understanding design and the computer. As part of this philosophy, "computation can be seen just one of many metaphors we have at our disposal for understanding design", and hence "if design is characterised as 'metaphor play' then the computer opens up possibilities for exploring design metaphors and possibilities as a tool for designers"[2]. Like Winograd and Flores (1987)[3], Coyne and Snodgrass (1993) assert that "computers are (and always will be) merely equipment". This contrasts with the viewpoint that sees computational devices as having the potential to replace the human agent in the design process.

If we consider the computer as a tool and as one of the design aids available to the designer, it can be evaluated on its usefulness (What is the interest of the model to the designer's activity?) and usability (Is the design system easy to use?). This idea of usefulness focuses attention on the roles of computer such as better design or faster design process, and the usability directs attention to the unconstrained environment for human-computer interaction. Such a change from a machine-centered to a user-centered view of computing leads the models of what machines do to become less important than models of what people do[4]. In this regard, a different theoretical framework for computerising the design process is required, which can be more amenable to architectural design than rational problem-solving one.

This study also started with the standpoints of aiming to establish a theoretical computational model for architectural design. To do so, I suggested *mental space* as a metaphor for the system inside the designer's mind. This metaphor is based on the designer's thinking/action and emphasises design activities rather than design cognition processes. Thus, this computational model focuses on how the computer helps the design process, not on how to solve a design problem. Next, I will identify that this model can serve as the sources of ideas for computerising designer's mental processes, and furthermore, for developing a design system.

7.2 Mental Space Computational Model (MSCM)

Mental Space Computational Model (MSCM) refers to a design computational model that attempts to mimic the various mental performances and processes occurring in the architect's mental space. As stated in chapter 6, the design mental process can be described as generating design ideas, designing in mental space and visualising mental images. It is fundamentally dissimilar to the memory-based information process that stores information and later retrieves it. Moreover, such internal representations are so vague, non-transible and personal that it has been, so far, impossible to represent them in computer memory system.

Accordingly, the application of the MSCM aims not to generate a design but to participate in designing, along with human agent, as a design tool. The success as a design system, therefore, depends on how richly and meaningfully the computer environment supports the architect in representing and visualising these internal processes. Here, based on a new understanding of computer's role as the metaphor of mental space, I attempt to establish the nature of the computational environment suggested by MSCM as follows.

(1) **MSCM facilitates the architect's mental exploring process**: The architect constantly represents or refines objects and events in mental space until they satisfies, with sketching, drawing or modelling their ideas and concepts. Thus, the system must not push the architect towards a developed design but should provide the facility to *transfer fluently from mental image to computer image*. This is the most crucial function in the mental space system and hence the MSCM must be established on the important observation about how the architect

internally represents his ideas and how he can visualise them on drawing board or computer screen (see, section 5.3.3 and 6.2).

(2) **It can enhance the architect's capacities for creativity and judgement**: Like the almost boundless space in mental space that furnishes designer's endless explorations, the computer also can provide the unlimited capacity for exploring design in virtual computer space with powerful graphic technology. In this context, the system can serve successfully as a design visualising tool, with which the designer can create freely new design ideas, represent them and test them against some criteria (see, section 6.4.2).

Another advantage of the computer is that it provides a significant capacity for storage and access of information. That is, the architect can arrive at reasonable solutions or decisions through rich design knowledge or externally stored information; furthermore, it is supposed that visual images of precedent designs can stimulate imagery effects that activate mental interaction between intuition and intellect. In this regard, the MSCM emphasises the reference function of computer memory system, rather than as an inference function (see, section 6.3).

(3) **It aims at more fast, safe and smooth design processes**: The common goal of design tools and methods is to achieve the effective design process and better design; MSCM also attempts to ease-use and to reduce the designer's tedious efforts in representing a design. Most of CAD applications and support programs are one-purpose applications, isolated each other. Thus, to be more than a mere drawing tool, CAD should furnish to transfer information more fast, safely between design applications as well as between design stages, by integrating the separated functionalities. Rather than to automate design process as a whole, it will be more feasible approach to program some repetitive or quantitative properties of design representations into database as pre-structured knowledge, rules, or intelligent agents. As a result, these computational environments, as seen in section 6.4.3, help the architecture to co-operate intuition and intelligent, and the computer can serve as the interface that furnishes interaction between them.

Simply speaking, the MSCM pays more attention to assisting designer's activities involved in computation, than to generating design solutions and decision. It does this by facilitating mental exploring processes, and by aiding the transfer between design stages smoothly. Its ultimate objective is therefore to augment the designer's knowledge and imagery for a better design result.

7.2.1 The Structure of Mental Space Systems

As seen above, the MSCM aims to support the architect in progressing design smoothly, from perceiving a design in mental space to expressing it on a computer. In computer system, mental space is analogised as design platform, which plays a main role in design computation. It combines design visualising tools with reference tools; while reference tools supply relevant information, design tools are used for representing mental images and concepts. Figure 7-1 shows the relationships between the structure of the designer's mental space and that of computational support system, in the light of the representations on mental space discussed in chapter 6.

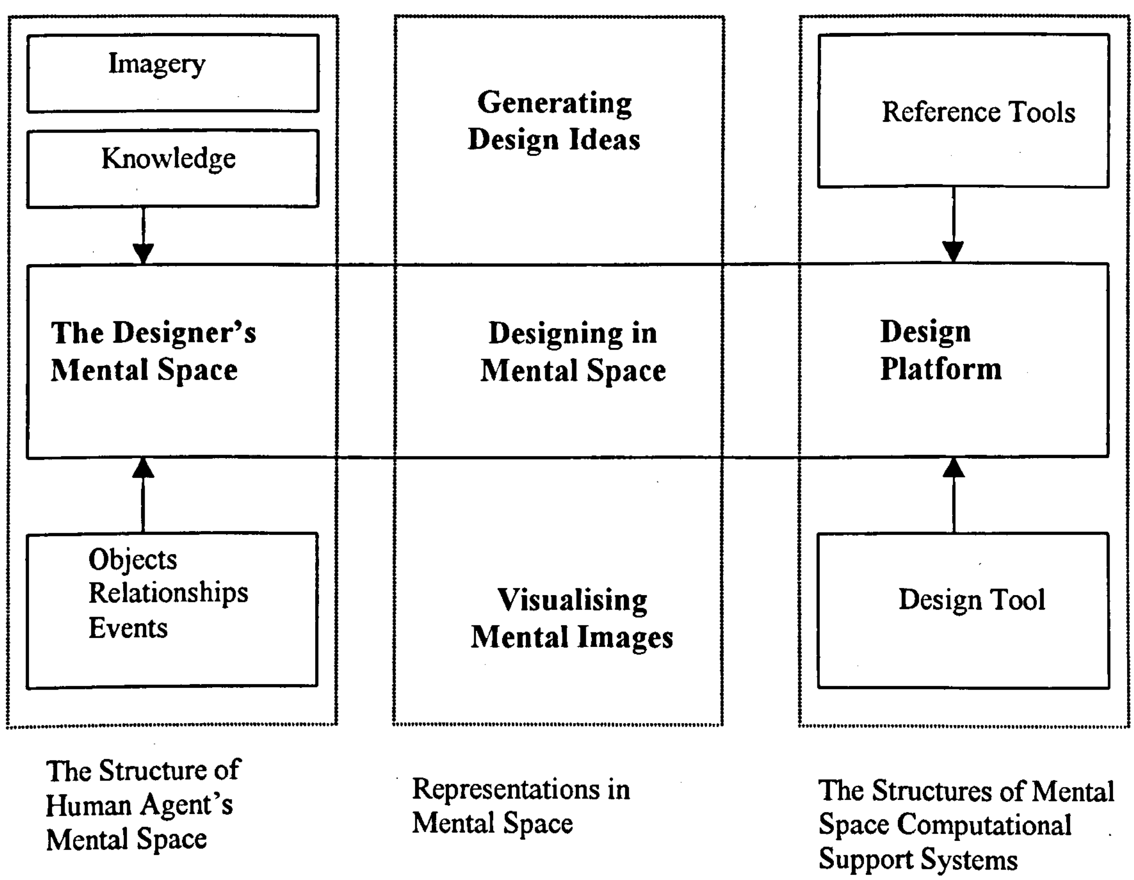


Figure 7-1: The relationships between the structure of the designer's mental space and that of the mental space Computational Support systems

Design Platform: The design platform is a physical metaphor of the designer's designing in mental space. As mental space is a medium for transferring internal representation into external process, the design platform functions as an interface in which the human agent communicates through the computer agent, and the designer performs actual design. The design platform will be 3 or 4 dimensional, boundless space that designers can explore their design world and experiment new ideas. In addition, it is a kind of organism that can be developed by the enhancement of the architect's abilities through exploiting the capacities of the computer, in it human mental space can be extended by enhancing capabilities for imagery and knowledge. Thus, the design platform should support the human-computer interaction in a way that takes full advantages of both capabilities of human imagery and computer memory.

Reference Tools: The basic premise of a reference tool is that most design information cannot be prescribed, because of its overwhelming volume and vagueness. Moreover, its utility is directly related to the situation and to the designer in that context. Accordingly, the mental space system does not attempt to generate design solutions, but aims to help the architect to enhance a knowing state or to trigger his imagery by providing a set of information, knowledge or design precedence.

In contrast with the contemporary systems that enumerate a number of information or a series of the structured design knowledge, if designers themselves could store their experience, could organise the structure according to personal preference, and then could retrieve this information at will, the usefulness and usability of information would be much improved. Thus, its computational environment includes the systems for information edition, store, and retrieval. In this way, the reference tool provides the architect with memory or imagery aids for a personal specific task, rather than for general design knowledge or information.

Design Visualising Tools: The drawing tool is the kernel of the mental space system, with which the designer translates internal representations in mental space to the outer world for self-conversation. As the design progresses, the designer evolves ideas through various graphic representation types – diagrams, sketches, schematic drawings and modelling. If such drawings are supposed to be real world enactments of mental representation, the design tools should assist the designer to visualise internal designing fluently via the design platform. Accordingly, the success of the mental space system depends on implementing the design visualising tools. So many drawing software are marketed and researched along with much sophisticated graphic techniques, but none of them, so far, helps actually the designer in every design stage.

Naturally, next discussion must be about how to computerise mental space, but this is not an easy task. Bijl gives another inspiration to form mental space system; "Ideally, in any implementation in a computer, *its structure should follow the content of expressions decided by the designer*, which has been the focus of research on design system over many years"[5]. According to this simple but hard agenda, I will examine the design contents that the design represents in mental space – objects, events and relationships, in order to draw some insight into establishing the new CAAD environment.

7.2.2 The Computation of Mental Space

For a design system to work, the constituents of design have to be descried by computer program. In the preceding chapter, I identified that mental space consists of symbolic representations of *objects*, *events* and *relationships*. In order to computerise mental space, these design contents should be represented into the design system as objects being designed, operational knowledge about relationship between objects, and events linking between objects and context.

Computerising Objects in the Mental Space Systems

During designing, architects deal with the symbolised mental images in their minds, and at the same time, they visualise through drawings or models in many different ways. In computer system, mental images are displayed to the viewer as objects. They are combined or refined in computer virtual space as well as in mental space, with describing forms and aspects of function, material, construction and so on. The objects therefore have their own properties such as geometric (location, shape or movement) and semantic (identity, function or the designer's value), as discussed in the chapter 6. Thus, design tools have to aid the architect in manipulating together the geometric and architectural properties of objects.

Below, I demonstrate some implications for the computation of design objects, and suggest some hypothetical applications based on mental space theory.

(1) **Appropriate design parameters and operators**: Designing is a process during which free-hand drawings develop into more concrete, scaled ones. Any design action is involved in one of sketching, diagram drawing, doodling, schematic drawing, detailed drawing, or three-dimensional modelling. Such drawings are performed in different ways, and hence each step has its own preferable parameters and operations. Thus, the first effort for design systems is to articulate the kind of symbol system the architect generates and use in his mental space (design parameters) and how they are manipulated (operators). Based on these examinations, the system should provide the easy-use tools and the more acceptable tools to architectural design.

For instance, as seen the case study in section 4.3, the architects represent very obscure images at the beginning stage and represent architectural properties as well as geometric information. They do not represent objects with abstract symbols such as a line, circle or rectangle, but rather they visualise them in terms of a space. This observation implies that more precise design tools rather hamper design development, and that space (such as a room, a class, or a unit) can be dealt with as an object in database or a primitive element as a design tool. That is, a graphic element and attributes of a space with an actual identity such kitchen, living room, and so on, can be structured in a database and manipulated as design elements.

(2) **Efficient design process**: One of the most important goals of MSCM is to facilitate more effective design process than that offered by the traditional pen-paper based tools. In mental space, the human agent travel freely among design steps, for example, from sketch to modelling; from 2 D to 3 D; or from layout plan to elevation drawings. While the traditional design methods perform these functionalities with very cheap cost and efforts, computer is still too clumsy to transfer between steps consistently, despite the powerful graphic image. Its worst reason is because each of CAD applications performs only a part of design processes and hence it even hinders to draw up and develop his ideas.

Accordingly, MSCM emphasises the integration of different functionalities of each drawing step by using technologies of computer science and AI. For example, if system can recognise the properties and relationships of objects (e.g., patterns, materials or heights of an object) by inputting semantic information or by activating them from database, it will help recognise hand-drawings drawing; to swap drawing from 2 D mode to 3 D mode in real time; even to estimate construction costs, and so on. Among them, todays, some functionalities are successfully performed, even though limited within a specific computational environment.

(3) **Tools for design explorations**: Another observation noted in chapter 6, is the explorative characteristics of designing; mentally architects continuously travel in two- or three-dimensional unbounded space searching for better design products. During explorations, they suggest possible designs and test them, comparing functions or appearance according to design criteria, the brief or value. Moreover, they handle manifold images at a time. Because a design idea effects all or many parts of designing and its consequence brings new problems to be solved. Thus, the designer thinks of a design as the whole or at least a number of issues at once and hence works with loose procedures. Schön (1985) called it, from his protocol analysis, a *principle* of design, in which the designer makes a design from the unit and from the total and then goes in cycles – back and forth, forth and back[6]. Such a loosely structured mental exploration is the critical challenge that a computer based design environment must enable someday.

(4) **Various perceptual experiences**: Mental images are the result of the designer's perceptual experiences. Such experiences can motivate imagery and it helps to create new properties, unexpected relationships or events in a context. That is, the designer's creativity results in the exercise of imagination[7], and imagery can activate the dynamic mental interaction between intuition and intellect and make the boundaries of abilities to his cognition and creativity much more extended. Thus, the computer can serve for a space in which the designer's creative intuition is nourished by suppling rich perceptual experiences.

Today, the advanced graphic techniques and dynamic interaction offer the computer-user new design experiences that traditional design tools could never make possible. It does so by exploring the use of computers to investigate the manipulation of line, form, pattern, and colour as basic design elements, which provide a better understanding of design choice. The computer cannot only modify quickly the mass and scale of objects but also can swap the effects of colour and texture of images, and hence it permits flexible analysis and evaluation on the design. Thus, on computers, colour becomes an element of design that can be used as the substance of design intuition along with line, form and texture[8]. Such a development of computer graphic image plays, and will do, a leading role in replacing the traditional design representation with computing.

Another advantage in using the computer is that it has the potential to furnish mental movement in an active four-dimensional mental space with animation and walk-through of architecture. Such computer images provide useful information that can trigger new inspirations and understanding. Unfortunately, they are used mainly for exploring and evaluating the designed space and form rather than during designing. That is, 3 dimensional modelling and rendering software is generally applied to complete and accurate objects. Development of these ideas is one of the computational goals that CAAD research must pursue in the near future. This is because, only when such environments can be easily manipulated in the early design stage, will the computer serve as a real metaphor of mental simulations and mental processes.

Design Relationships and Events in Mental Space Systems

How can the relations and events be computerised? While a set of graphic design tools and operators manipulate the objects and its properties on computers, both relations and events are represented as a schema in some systems, and they do indirectly effect on the design procedures and design product.

Some relationships between objects, or between object and property information can be expressed as the logical form such as rules, mathematics or as a hierarchical network. This information is easily structured by formal languages and represented as knowledge in reasoning systems, and functions by operating the design procedures, or evaluating a designed object against criteria. Thus, it may reduce the number of time-consuming design iterations and improve the efficiency of the overall design process.

However, by contrast to the anticipations of the early CAAD research, relationships in architectural design are so loosely associated each other that they are not enough to infer some results or to solve a problem as a significant design process. As a result, such information can contribute to the architectural design process for some limited tasks; for example, a routine design layout (e.g., KAAD[9]), building analysis – energy, daylight, cost, structural and functional analyses (e.g., KNODES[10]); or recognising drawn objects and patterns (e.g., Electronic Cocktail Napkin[11]). Likewise, more recent views of human problem solving and cognition have generally emphasised on the role of more specific information associated with particular contexts[12].

Meanwhile, event-like information is more appropriate for architectural design systems. It is context-denpendent and is represented, usually in both verbal and pictorial form, from personalised experiences. In contrast with rigid information, it opens to other cognitive activities such as analogy, metaphor, intuition or even creative thinking as well as reasoning, which play a crucial role in design thinking.

In design systems, event-like information is encoded in highly specific knowledge in the form of cases, episodes, precedents, examples or references. These forms are more practical to deal with the incomplete and uncertain knowledge that describes how to design, along with the auxiliary verb '*may*'. This approach thus yields a reference tool rather than an intelligent design system. That is, the user (the architect) records experiences and knowledge useful for later use, and retrieves them when needed to verify proposals, to adapt old solutions, to interpret new situation, or to solve the problems posed. Accordingly, such system concentrates on organising, authoring and retrieving information, in order to provide designers with appropriate information, effortless access, and rich environment enough to trigger human imagery.

In this section, I attempt to account for how mental space is computerised and to suggest the hypothetical mental space systems, by mimicking the representations of objects, events and relationships that are the main substances in the designer's mental space. Some have been already integrated into commercial CAD applications, but most are still the subjects of research for the future. Thus, I am convinced that the deeper examination of mental space will lead to further insights into the appropriate development of computation of design.

7.3 Mental Space Approach to CAAD: Case Studies

In the preceding section, I suggested a mental space computational model, based on a theory of mental space; and I exemplified some possibilities of mental space as a computational metaphor. In order to examine these hypotheses as a new theoretical framework for the computation of architectural design, it would be ideal if a prototype computer system is offered and its feasibility is tested.

However, implementing all of the mental processes required to respond to the needs of mental space theory in a computer is still a long way off. It may be beyond the scope of today's computational techniques, but may, in the future, become possible through improved techniques and the accumulated research in CAAD related fields. Accordingly, instead demonstrating a Mental Space system, I briefly explore the existing or on-going research design tools, reference tools and integrated systems, which are related to the MSCM.

In the following sections, I have considered generic types of design support software, and within each generic type, particular software packages. These are reviewed from the point of view of establishing what they aim to achieve and how they fall short of the goals that are set by the requirements of a true mental space model environment suggested.

7.3.1 Design Tools

Firstly, a mental space system infers a design system that can interact with the mental processes effectively and smoothly. Among the mental operations in mental space (see, section 5.3.5), although generating design ideas will still remain in the human hegemony, computers can assist the designer in designing mentally and in visualising mental images, and can enhance thereby design potential. In particular, the design activities related to the visualisation have been, to some extent, successfully implemented in current computers.

However, the design mental processes do not occur separately in mental space; they actually occur simultaneously or randomly as seen in chapter 5. In contrast with the traditional pen and paper sketching or drawing, no computer environment so far accommodates such mental processes adequately. That is for the main reason why, in reality, computers are not used by designers, at least not when they are designing, although many commercial CAD programs have continually increasing functionalities and advancing graphic techniques. Here I demonstrate some commercial and academic research's efforts to achieve more-than-drafting tools.

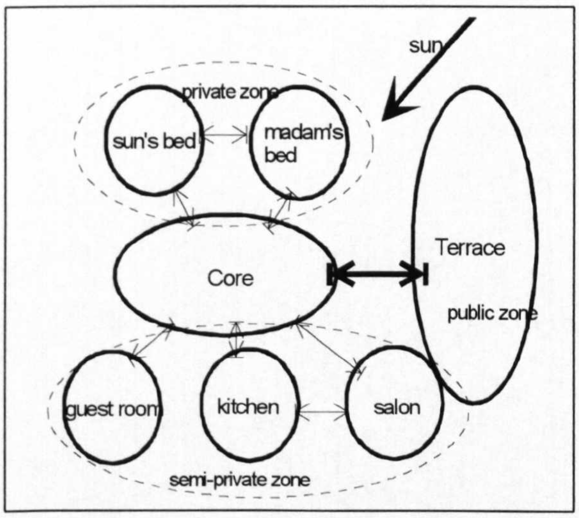
Design Sketch Applications

As a conventional design method, sketch (including diagram, doodle, design notes or scheme) is a very versatile tool with which the architect can represent mental images. It is not final description of completed designs, but is a medium for design process. Because of its easy-to-use properties, many architects engage in sketching (with, for instance, paper and pencil). This old design tool has served to test alternatives, to visualise metal images, and eventually, to help proceed the mental processes smoothly, with low cost and effort.

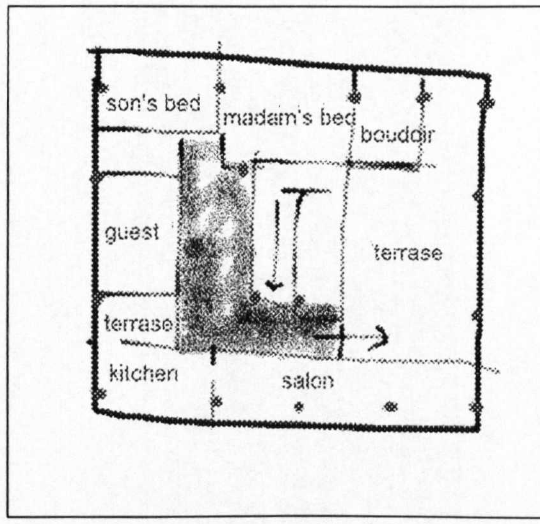
Most models for computer based sketching have tried to mimic the sketch process on computer with the conventional CAD methods, such as freehand-drawing applications or the electronic pens on LCD tablets, but they are still deficient as a visualising design tool. McCall (1997) points out the advantages of the conventional hand sketch, compared with CAD based drawing, such as the indeterminacy, non-destructive of drawing process, multiple inter-related drawings and transparency[13]. Thus, the future feature of drawing tools may be both to overcome such shortcomings and to allow the system to move towards what is required to achieve a mental space model.

Figure 7-2 compares a hypothetical computer-aided sketch process with the conventional sketch process, as implementing some sketch applications. I hypothesize the process consists of diagrammatic representation, rough sketching, schematic drawing and drafting. As showed in figure 7-2, I must choose different one for each step. That is because the existing commercial software has been developed for the specific purpose of drawing production and manipulation within a single process. For example, while general painting software (such as PC Paintbrush™, Paint Shop™ or CorelDraw™) is suitable for diagram and rough drawings, the CAD software such as Autosketch™ or Imagineer™ can be used for schematic drawings.

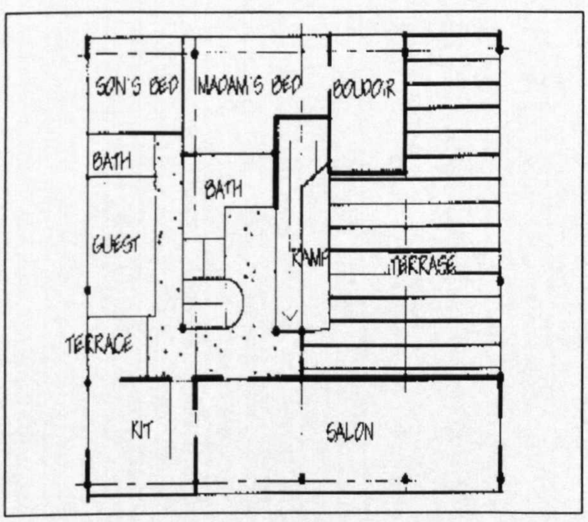
But, I experience that most of them require commitments to precise shape, position, dimension, and impose a rigidly structured procedure for creating and editing drawings. Such a line-centred concept and rigid processes restrict the architect in visualising and developing design ideas. Moreover, in order to proceed a next drawing step, the generated rough images must be redrawn with other drawing programs or three-dimensional modeller.



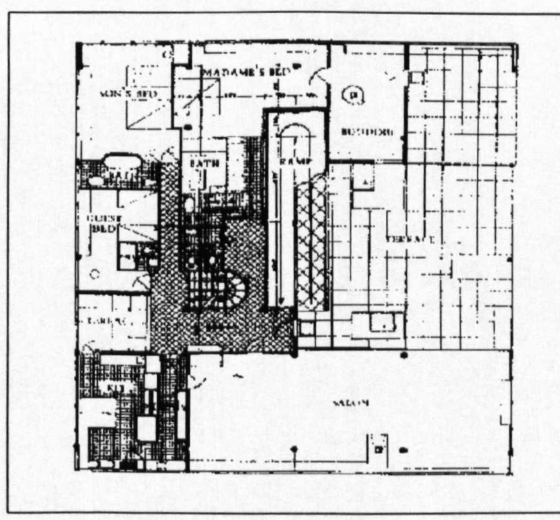
a) Analytic diagram: drawn with Micrografx Designer™



b) Rough sketch: drawn with Paintbrush™



c) Schematic drawing: drawn with Imagineer™



d) Detailed first floor plan of the Villa Savoye (from W.Curis p.95)

Figure 7-1: A hypothetical computer supported design processes of Le Corbusier's Villa Savoye: transferring from diagram drawing (a) to rough sketch (b), schematic drawing (c), and scaled drawing (d).

This is actually a time-consuming process. Even though more advanced methods such as tracing with a digitizing tablet and scanning a drawing can be employed, both methods require special software, devices and the limit of drawing size; and the designer cannot evade some new learning and reorganization if they are to convert a sketch into a formal drawing.

As a potential alternative, Imagineer™ provides a new functionality that can intelligently recognise smartly the rough shapes in sketch and turn quickly the sketch into a precise drawing. Although it is still awkward to be employed in the practice architectural design, if it can recognise a *finished* sketch or diagrams and convert them to a scaled drawing, this functionality may contribute remarkably to enabling design to proceed design fluently.

For example, in the analysis process of a diagram drawing stage (figure 7-2 (a)), either circle or rectangle may mean a space; and the arrow symbolises the relationships between spaces. Thus, if the system recognise these geometric meanings, it can be automated to transfer from diagram drawing to more detailed drawing stage (figure 7-2, (b), (c), and (d)) without redrawing each piece. In order for such processes to be performed in a single application, of course, a prerequisites is to generalise the various personal-drawing conventions and to devise the sophisticated recognition technique for selecting main lines among sketch lines or forms.

In the similar vein, Gross (1994) has been developing a pen-based drawing program (the Electronic Cocktail Napkin) that can recognise drawn diagrams[14] and automatically map the recognised diagram with Archie[ii] case-base or other knowledge-based system[15]. Though being based on empirical studies, their research has captured well how the designer designs and what tools and support they need in the sketch stage. In addition, it opens the meaningful use of knowledge (or case)-based system in supporting the conceptual design by inferring from the designed diagram.

In the other hand, most sketch applications use the line-based or point-oriented drawing method, and some software provides drawing libraries, sets of parts that can

[ii] Archie is the name of a system developed at Georgia Tech, USA, which embodies a database of design cases.

be assembled into drawings. As discussed in section 7-2-2, the architects represent ambiguous images in mental space, and visualise them in terms of a space (such as a room, a class, or a unit) as a graphic element rather than lines, points or fixed objects. Thus, the graphic element and architectural information of a space can be structured in a database and manipulated as design elements in a flexible way.

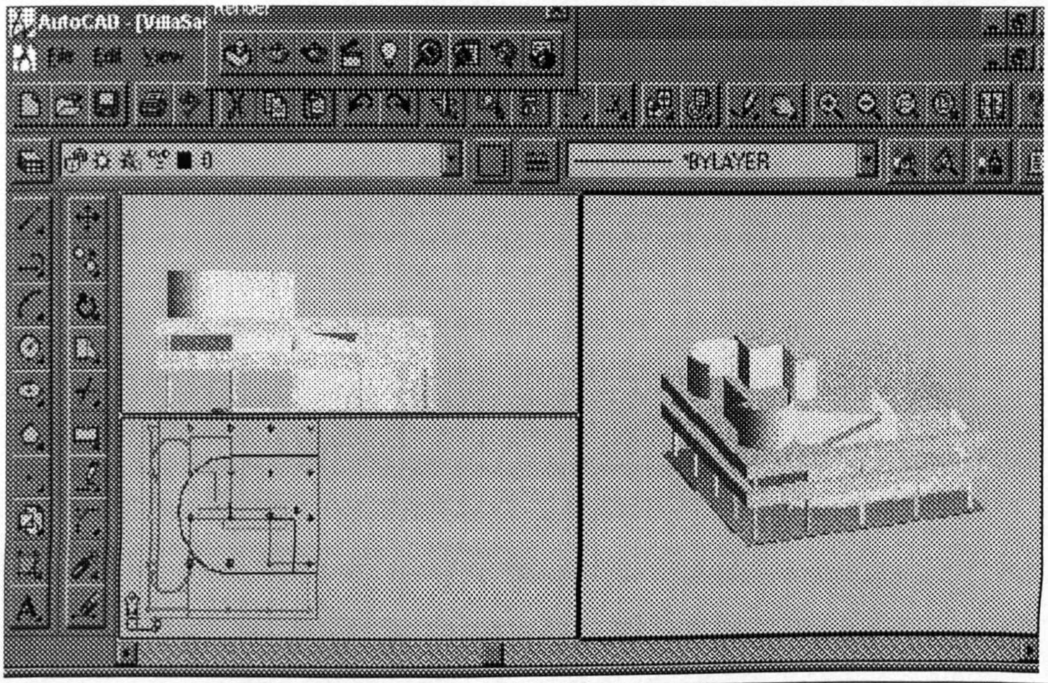
3Dimensional Modelling Applications

The design thinking/action can be seen as a visualising process, in which mental images are transformed from initial conceived state to its final form or space. While sketch deals mainly with 2 dimensional planning such as layout, rough elevation or section drawing, modelling is employed for the 3D design presentation and after, to some extend, making decisions about 2D design. Sometimes, especially in the cases that the appearance of building is a critical issue, the architect starts with 3 dimensional images and then develops them into floor plans or elevations. During this process, modelling is another useful design tool that can assist to externalise, explore and check the volumetric images.

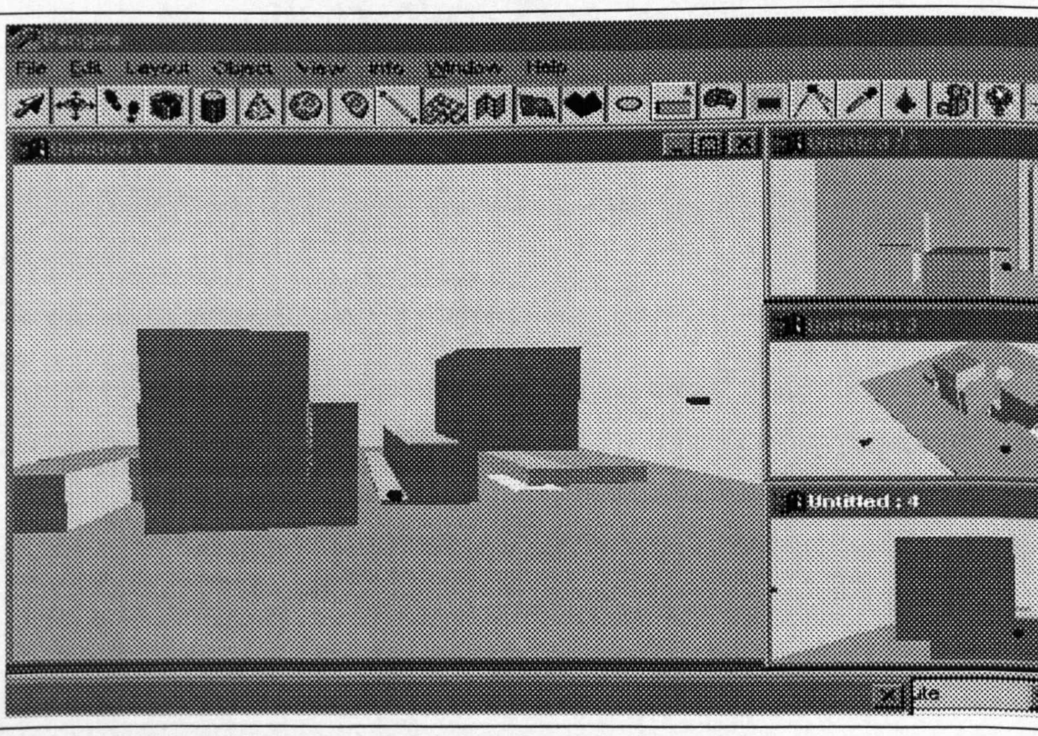
In contrast with sketch tools, computer-aided modelling has been much more improved since 1980s, equipped with realistic graphic and animation tools. Unlike small physical models, it can be used to add detail, develop nuances, conduct shadow studies, and explore interior-exterior relationships without relying on elaborate renderings or resorting to two-dimensional representations[16]. Modelling tools enable the designer not only to represent real images of designed objects but also to travel through the virtual world using virtual cameras. Moreover, the photographic colours, textures, lights and free movements lead to various perceptual experiences that can trigger new imagery. Accordingly, computer-aided modelling tools have become one of the significant new design tools for the practice-based architects.

However, most sophisticated commercial modelling tools like AutoCAD™ (see, figure 7-3) or 3D Studio™ require more precise and complex operation, and the process is laborious and needs special skills to convert from preliminary sketches or drawings. The design must be done in detail before modelling starts, and thus they generally are usually used for the post-design phase.

Accordingly, less precise, simpler tools equipped with the functionalities of direct manipulation and reliable operations are desirable for the designer to explore and evaluate design decisions by switching continuously between 2D and 3D simulation.



(a) Le Corbusier's Villa Savoye modelled by AutoCAD 13™.



(b) The computational environment of Pangea

Figure 7-3: Examples of 3D modelling computational environments for architectural design

It should be able to not only manipulate objects simply, but also change easily from 2D to 3D mode by using the functionality that displays several 2D and 3D views in a screen and shows the changes in real time. These approaches can provide a 3D computational environment closer to the incidental, random and manifold explorative mental process that is the most distinctive feature of architectural design.

ModelShop™ can be used as a modeller closer to these concepts. It aims at the early architectural design stage (maybe the first application for the basic model building applications), but is still with restricted geometry and low-key presentation. More recently, the attempts to devise a more sophisticated modelling tool for the early stage have been going on by some CAAD researchers. Among them, Kurmann *et al.* (1997) have devised the powerful modelling tool – Sculptor[17], which facilitates modelling, presenting, testing and developing the spatial components and enables the architect to design interactively with computer in 3D space. It is possible to make directly changes and to immediately view those changes, by using Boolean solid modelling techniques[iii]. In addition, the design assisting agents - the navigator, the sound, and the cost agent - support the designer by providing information and executing background tasks. The strong point of this program is the powerful performance with simpler, more intuitive modelling abilities in real-time, with which the architect can explore ideas freely in the virtual space.

Meanwhile, Pangea[iv] (see, figure 7-3) adds intelligent tool kits for decision support to the simple 3D visualising tool. It is suggested that its tool kits can solve design problems by using Generic Algorithm and Morphic Search tool, for example, to find the best layout, to minimise heat loss, or to optimise image rendering[18]. Even though such functionalities seem not to operate as successfully as they anticipated, this approach to the integration of graphic tool and intelligent tool is of great worth for computer to be a significant tool for architectural design.

[iii] They draw the concept of positive (solid) and negative (space) volumes, instead of general Boolean operations like subtraction, union, difference, interaction or split.

[iv] **Pangea** is intelligent 3D modelling program, written by the intelligent architecture project (from 1994 to 1996) at UCL (University College London).

7.3.2 Descriptive Reference Tools

Throughout this thesis, I have argued that the prescriptive knowledge-based system is inadequate for architectural design with a few exceptions, since design information and operations cannot be made explicit in the same way of structuring knowledge. How, then, can the design system benefit from the immense advantage of the computer memory system? I propose a descriptive[v] reference tool, which may be more feasible for design domain in the light of the current computational techniques and the characteristics of design itself.

This approach starts from the observations; when the designer feels the limitation of intelligence or intuition, they might review some design magazines, design standards, idea notebooks, and so on, for new knowledge and inspirations. In addition, they might sometimes resolve the design problems out of the retrieval, adaptation and refinement of the past design precedents. Accordingly, the descriptive reference design tool aims at making these design activities easier in finding, browsing and learning from the repository of relevant information; and hence helps the designer's mental space more expanded and generating a more creative design.

Thus, the system focuses on how usefully the information organises and how easily the user retrieves them. Design is not an artefact inferred from facts, but responds to with experiences of design. In this context, design information refers to 'recorded experience' belonging to a specific situation; and should be represented as a whole, in the form of an event and by personal conventions. Strictly speaking, no one knows what kind of information is needed or available for a situation more than the architect him/herself. That is, it may be meaningless for anyone other than the architect to anticipate and prescribe such idiosyncratic design information into a general computer system.

Consequently, the descriptive reference tool furnishes a prototype of a memory system, in which personal experience information can be accumulated by authoring tools. It enables the user to freely construct his experience according to his

[v]Bijl (1989) argues in *Computer Discipline and Design Practice*, the prescription and description of computer system. He defines 'description' as expressions and 'a description system' as one which people can use to produce and modify their own expressions.

preference and needs, and to recall easily them by non-linear, random accesses. This approach becomes more feasible, when associated with the recent advances that allow the inclusion of graphic, animation and video as well as textual material, such as Hypertext or Hypermedia.

In the design domain, hypertext has been used for the documentation of design standards and codes[19] or the design information systems[20]. Its main advantage lies in the capabilities of browsing and authoring; the user can access desired information and can easily update them. IBIS (Issue-Based Information System), developed by Rittel, was the first attempt to construct design information and processes by using the hyperlink functions like non-linear and navigation[21]. Along with the improvement of such software and hardware storage, many design information programs employing hypertext and hypermedia have been proposed.

Among them, HyperCard™ is the most popular hypermedia authoring software, capable of storing text, graphics and sound in its nodes[22]. Hypermedia software provides many potentials to design applications. These applications have been employed in representing design cases for some case-based design aiding systems as seen in the chapter 3.

In this way, hypermedia (or multimedia) software can prompt a reference tool enough to author and retrieve design information. That is, this medium allows the architect's various visual or cognitive experiences to be integrated though free sketch, video, camera or word-processing. Accordingly, rather than simply providing information about principles and verbal descriptions of examples, the reference tool can suggest graphic events or cases that the architect previously encountered in particular types of context, such as a set of plans, perspective drawings, animation, virtual space and even sound.

Thus, these rich visual images and lexical information on computer screen can let the designer experience sensible qualities: colours, sounds, feeling, and the shapes and positions of objects in an environment, and eventually they augment imagery and intuition, as well as amplify intellectual capabilities. That is, it permits the designer not only to browse freely relevant information but also to enable to the discover new, often unexpected, concepts in precedents[23]. Figure 7-4 demonstrates a descriptive design reference tool, exemplifying a case of Le Corbusier's Villa Savoye.

However, such a computational environment is deficient for the real design process, unless it interacts with the drawing tools. The reference tool should be integrated within drawing programs for the designer to gain easy accesses to right information at right time. That is, during a drawing session, the designer can invoke relevant information in the same manner as any other CAD operation. This integrated computational environment can support the designer to review the designed 2Dor 3D models, to advise a particular design problem, or to check for all relevant criteria.

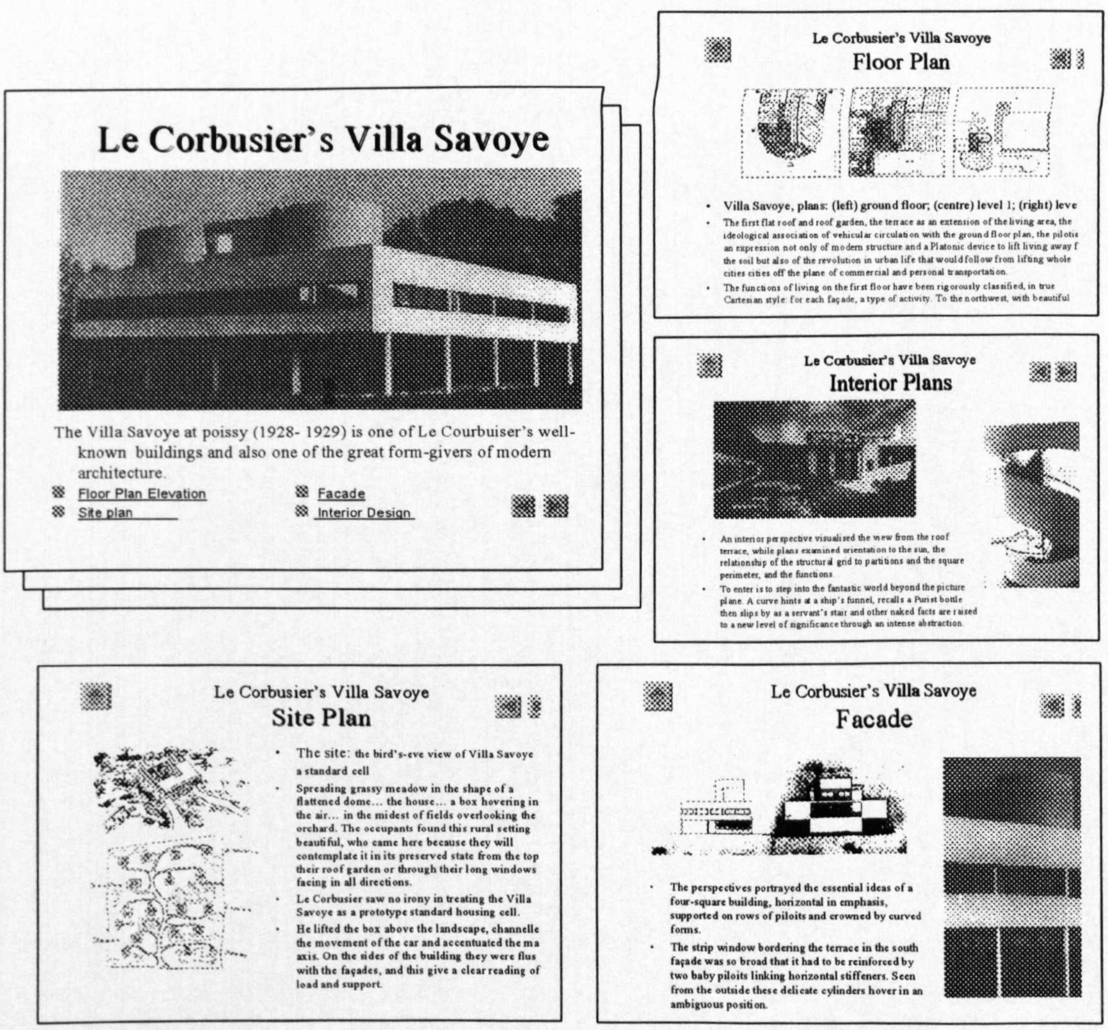


Figure 7-4: An example of a descriptive reference for architectural design

7.3.3 Integrated Mental Space Systems

The enthusiasms for an integrated system have persisted through CAD history, but still are not achieved. Bijl (1989) defines an integrated design system as one that employs a single model to accommodate all information describing design objects to support a range of tasks[24]. However, it is impossible, at least with todays computational technology, that all design information can be represented in an explicit manner in a design system.

The one of the reasons for the failure of the integrated system may be their strong enthusiasms to force computers to solve all of the design problems, to perform the entire design processes, and to generate something significant to design. In this regard, I suggest a partial, but more practical, approach to the integrated design systems in this section. To do so, I demonstrate some factors that should be considered for the integrated system – dimensional, design procedural, functional and multi-disciplinary integration.

Dimensional Integration: The architect creates a space by embodying new function and form to an empty environment. Here, they reconcile the conflicting elements between forms and functions of space by exploring its 2D, or 3D space. In this process, they experiment continuously whether or not their proposed ideas actually fit the goals of the task, and evaluate a number of alternatives against criteria.

In this context, the design system should help the user to manipulate and explore various dimensional spaces easily and smoothly. To meet the demands, design sketch tools and modelling tools are amalgamated in a stand-alone program, and hence the drawn objects come and go between 2D to 3D or 4D, more intuitively and in a less precise computational environment.

Design Stage (Functional) Integration: Most CAD programs have been marketed and researched for single design process – sketch, schematic design, drafting, modelling, presenting, evaluating and so on – with different technical and theoretical background, and with different functionalities for each. As seen in the previous sections, design is constituted of random, incidental explorative processes so that the integrated systems should enable the designer to make a design as a whole process and to gain access more easily to all functionalities of each application.

This has been investigated by combining the existing computer techniques or applications with one another; for examples, (1) by combining similar functionalities as a CAD package, (2) by combining database system with CAD applications[vi], or (3) by combining CAD programming with logic programming of AI. The approach of (1) has been already undertaken and commercialised by the big CAD companies. The method of (2) has been researched by the data modelling communities, and that of (3) has been employed by AI in design fields. Both use an object-oriented approach, aiming towards the development of an integrated semantic design representation – each as a data model or as a knowledge representation.

As an example of the approach to integrating CAD and AI technology, Brown *et al.* (1997) propose an architectural environmental analysis application by embedding an intelligent program (SPARTA: SPAtial reasoning using Tesseral Addressing) into 3D package[25] (see figure 7-5).

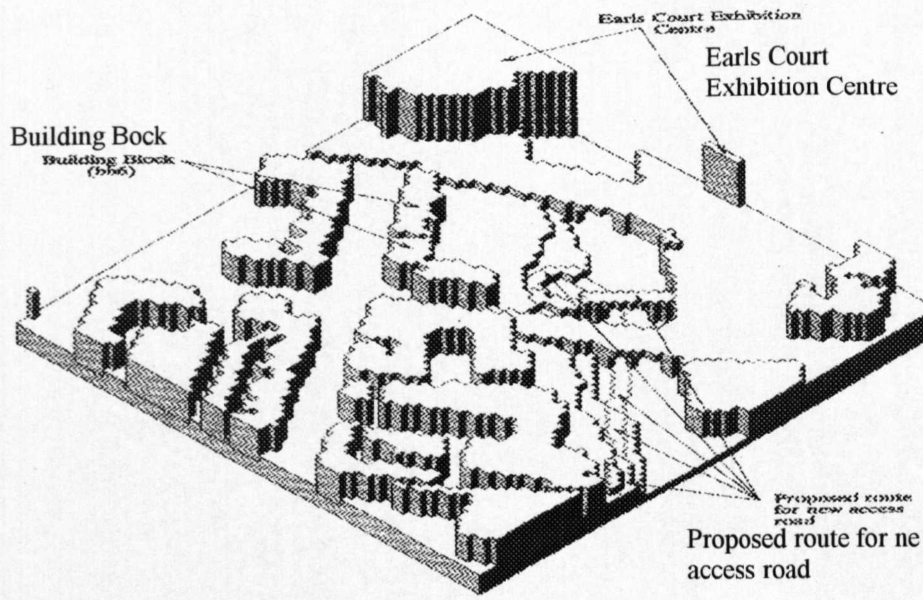


Figure 7-5: The tesseral representation of the site objects in order to analyse a built environment problem.

That is, the embedded knowledge-based system can obtain design information by exchanging data of geometry and attributes of the CAD model, and then its

[vi] For example, Eastman and Lang (1991) proposed 'object based modelling (OBM)' as the means for representing design semantic information, in 'Experiments in architectural design development using CAAD' in Proceeding of *CAAD Futures '91*, G. Schmitt (ed.), Wiesbaden: Vieweg, pp. 49-64.

inferencing process occurs as the result of rule execution. It can operate directly on the CAD model, by reading, creating, modifying, or manipulating geometric or non-geometric data.

However, since the geometric descriptions created by current CAD systems are essentially limited to points, lines, faces and shapes, it is still quite difficult to generate higher level information (semantic information) from such lower level information[26]. Moreover, such an approach would require basically to describe the design operations into some design rules in order for the inference engine to accept them, and. As a result, it is applied only some limited parts of design sub-problems, and is impractical until a graphical language for expressing rules and constraints is developed[27].

In this regard, rather than the two descriptive approaches of (2) and (3), the first approach to amalgamate the applications containing similar functions seems to be more feasible at present and more promising for the future. That is, it would be better for designer that 2D and 3D space can be explored freely and can represent objects and its relations smoothly, by integrating the functionalities of sketch, draft and modelling applications into an integrated design visualising tool. In these systems, design knowledge can serve as an auxiliary tool to drawing, for example, to recognise design patterns or to automate some tedious, repetitious drawing operations.

Multi-User Integration: In the architectural design process, various workers take part, such as clients, engineers, constructors, technicians, as well as architects. Integrated systems can serve as a medium of communication, and as the base for the collaborative, multi-disciplinary design environment. Currently a great deal of CAAD researcher is being done on these environments, such as by sharing the drawing surface[28], by semantic modelling of multi-disciplinary design[29] or by shared virtual reality technology[30] on the web site.

Such techniques can support as evaluation tools after, or during design. For example, as the designer produces some alternatives, other participants in the project could take part in this evaluation phase by the telecommunication technology like web-based interactions or video-conference. Even though I did not consider the social, communicative aspects of designing in this thesis, this aspect must be considered in developing an integrated system of this kind.

7.4 Mental Space System

In the previous section, I have explored some applications associated to a mental space computational model (MSCM) proposed in section 7.2. As seen in case studies, even though some design processes have already been successfully computed, through various forms of analyses and visual representations, there exists, so far, no computational environment that fully supports and facilitates the architect's mental operations in mental space. Most applications for architectural design are used for post-design; they have severe limitations to support the explorative characteristics of design, and hence rather hamper generating associated images and developing design ideas. In this regard, mental space theory is suggested as an alternative theoretical framework for a better design computational environment. Here, I need to make more clear what the mental space system might look like; what this system intends to achieve for the computation of architectural design.

Simply speaking, the Mental Space system refers to a design system that can mimic mental operations in mental space, which is where design thinking-action takes place. Firstly, it can be distinguished from a memory-based system. This thesis classified the designer's mental mechanism into memory, mental space, and interface. Among them, while the interface is posited as the domain of the human agent, the memory system and mental space can be considered as a computer environment that supports the designer. But designing is not solely involved in problem-solving, decision-making or cognition-dependent activities; rather it depends more on the designer's experience, and skills in imagery or graphicacy. Thus, this system attempts to accommodate the mental operations occurring in mental space rather than knowledge organisation in a memory system, and focuses on how the designer processes mental images and consequently how they are represented in computers.

Secondly, the Mental Space system should support the designer in the early design stage, where the most important features of a design are established. This stage requires efficient support for the associated dynamic cognition and creative processes. In this process, the designer continuously moves between 2D and 3D, or even time-dimensional unbounded space searching for a better design. Thus, this system should provide the designer with a computational environment that is capable of visualising objects imagined in mental space in a variety of representational formats for example. It must be easy to move between different representations of drawn objects from planing to elevation or from 2D mode to 3D mode in real time.

Furthermore, the developments in visual representation of digital images such as virtual reality (VR) and 3D TV provide a potential new alternative design working space where the designer can manipulate mental representations in more flexible and multifaceted way than a conventional flat computer screen can. Such a computational environment would help the designer to exercise the various perceptual experiences that I have discussed, and this should then activate a more productive mental interaction between intuition and intellect.

Thirdly, to make computers a more useful tool, the interface of a mental space system should aid the designer's eye-hand-mind interactions. Therefore, one of the most critical tasks is to fill the current gaps between the designer's representation and computer representation and to recognise the different attributes, strategies and methods appropriate to different representations. For example, the former refers to representing mental images in mental space, and it is represented in obscure, pictorial and space-based drawing ways; the latter is used for externalise the completed images and concepts, and it is represented visually in precise, verbal or 'point-oriented drawing ways[31]'.

The designer's mental images consist of 2D spaces or 3D volumes, but generally, the computer still requires its elements specified as geometric primitive such as point, line, cube, sphere, circle and so on. Such a fundamental difference interrupts the smooth connection between the hand-eye-mind environment that a mental space model seeks to achieve. To assimilate the necessary components, first of all, we should pose the space-based or volume-based concept in considering a design visualising tool rather than the point-orient approach.

On this standpoint, the design system should provide the easy-use interfaces and the readiness-to-hand functionalities that are particularly appropriate to the architectural design mental process, such as, simplicity; visual immediacy; multi-faceted visualisation; immediate feedback and dynamic interaction. Furthermore, what us needed is to develop an environment that can transfer mental images safely and smoothly between eye, mind and hand; one which can promote exploration and discovery, and which can enhance the potential of the designer's creativity and imagery.

Lastly, the mental space system is an integrated computational environment. It aspires, to support all design thinking-action activities, such as dimensional, functional, design procedural, and multi-user integration. In this respect, the computer is employed as a simple supporting tool for visualising mental images (a design visualising tool) and supplying relevant design information (a descriptive reference tool). Such a man-machine symbiosis environment can lead the designer to a more efficient, reliable productivity, and in turn, this can allow the computer to partake in the creative process by augmenting the capacities of the designer's knowledge and imagery capabilities.

7.5 Discussion

In this chapter, I have examined the feasibility of mental space as computational metaphor and considered its potential as the basis for an architectural design system. In doing so, I suggested a mental space computational model (MSCM), which attempts to mimic and thereby support the mental operations and processes occurring in the architect's mental space. This computational model aims to accommodate the design phenomenon of thinking-action.

Accordingly, the mental space system emphasises design activities rather than design cognition processes and the capabilities of the computer rather than the computability of design. The result would be an integrated computational environment for the early design stage, in which the designer makes and changes design objects, relationships and events smoothly, quickly and with appropriate feedback, in contrast with a memory-based system that works with pre-structured knowledge. Thus, the mental space approach to CAAD would emphasise the mental operations in mental space rather than memory organisation or retrieval in a memory system. It would aim to implement design thinking/action rather than design cognition, and would focus on the role of imagery rather than that of knowledge in the design process.

Nevertheless, the development of the mental space system is a matter for much research and evolution. Even though I have articulated the required representation in mental space, this thesis did not make specific recommendation as to how they can be represented in computers as operators, parameters, and databases. The difficulty lies in representing mental images with computer languages, because of the features of mental images such as their uncertainty, ambiguity, variety, and accidental nature. These studies will be my further research subject.

As a conclusion, I believe that the mental space approach can contribute CAAD research to providing rich implications for a better computer-based design environment. That is, the deep observations of mental space will lead computers to accommodating design activities more appropriately, and to be thereby more acceptable to the designer. I believe that such a computational environment, someday, will be willingly chosen as a creative design tool instead of the traditional pen-paper tool in the design process.

Reference

[1] Greence, J., *Memory, Thinking and Language*, Methuen, London, pp.3-4, 1987.

[2] Coyne, R. and A. Snodgrass, 'Rescuring CAD from rationalism', in *Design Studies*, Vol.14, No.2, pp. 100-123, 1993.

[3] See, Winograd, T. and F. Flores, *Understanding Computers and Cognition*, Addision-Welsey Publishing Company, Inc., Reading, 1987.

[4] Allemang, D., 'Combining case-based reasoning and task-specific architectures', *IEEE EXPERT*, Vol.9, No.5, pp. 24-33, 1994.

[5] Bijl, A., *Computer Discipline and Design Practice: Shaping Our Future*, Edinburgh University Press, Edinburgh, p. 80, 1989.

[6] Schön, D., *The Design Studio*, RIBA Publications Limited, London, pp.30-52, 1985.

[7] Pateman, T., *Key Concepts; A Guide to Aesthetics, Criticism and the Arts in Education*, The Falmer Press, London, pp. 78-80, 1991.

[8] Norman R.B., 'Intuitive design and computation', in *Computability of Design*, John Wiley & Son, New York, pp. 295-301, 1987.

[9] See, Carrara, G., Y.E. Kalay and G. Novembri, 'Knowledge-based computational support for architectural design', in G. Carara and Y.E. Kalay (eds.), Elsevier, Amsterdam, pp.147-198, 1994.

[10] See, Rutherford, J.H. and T.W. Maver, 'Knowledge-based design support', in *Knowledge-Based Computer-Aided Architectural Design, op. cit.*, pp. 243-267.

[11] See, Gross, M.D., 'The fat pencil, the cocktail napkin, and the slide library', in Proceedings of *ACADIA 1994*, A. Harfmann and M. Fraser (eds.), pp. 103-112, 1994.

[12] Purcell, A.T., J.S. Gero, H.M. Edwards, and E. Matka, 'Design Fixation and intelligent design aids', in *Artificial Intelligence in Design '94*, J.S. Gero and F. Sudweeks (eds.), pp. 483-495, 1994.

[13] McCall, R., E. Johson and M. Smith, 'HyperSketching: Design as creating a graphic hyperdocument', in *Proceeding of CAAD futures 1997*, R. Junge (ed.), Kluwer Academic Publishers, pp.849-854, 1997.

[14] Gross, M.D., 'The fat pencil, the cocktail napkin, and the slide library', *op.cit.*, pp. 103-112.

[15] Do, E.Y., 'Computability of design diagram', in Proceedings of *CAAD futures 1997, op.cit.*, pp. 163-170. and 'What is in a diagram that a computer should understand?', in *Proceeding CAAD futures 1995*, M. Tan and R. The (eds.), National University of Singapore, pp. 469-480, 1995.

[16] Crosley, M.L., *The Architect's Guide to Computer-Aided Design*, John Wiley & Son, New York, p. 138, 1988.

[17] Kurmann, D., N. Elte and M.Engeli, 'Real-time modelling with architectural space', in Proceedings of *CAAD futures 1997, op. cit.*, pp. 809-819.

[18] Penn, A. *et.al.*, *Pangea V2.1b: User's Guide*, UCL, pp.39-58, 1997.

[19] *see*, Cornik, S. M., 'HyperCode: The building code as a Hyperdocument', *Engineering with Computer*, Vol. 7, No. 1, pp. 37- 46, 1991.

[20] *see*, McCall, R. J., 'MIKROPLIS: a hypertext system for design', in *Design Studies*, Vol. 10, No. 4, pp. 228-237, 1989.

[21] Conklin, J., 'Hypertext: An introduction and survey', *Computer*, Vol. 20, pp. 17- 42, 1987.

[22] Cotton, B. and R. Oliver, *Understanding Hypermedia*, Phaidon Press Ltd., London, p. 143, 1994.

[23] Oxman, R. and R.M. Oxman, , 'PRECEDENTS: Memory structure in design case libraries', in *CAD Futures '93*, U. Flemming and S. Van Wyk (eds.), Elsevier, Amsterdam, pp. 273- 287, 1993.

[24] Bijl, A., *Computer Discipline and Design Practice: Shaping Our Future*, *op. cit.*, pp. 81-115.

[25] Brown, A.G.P., M.Knight, F.Corenen and P.Geraghty, 'Representation and reasoning in architectural space: a linear tesseral approach', *Proceedings of ECAADE Conference 1997*, T.V.Wien (ed.), Viennd, September, 1997.

[26] Pohl, J. and L. Myers, 'A distributed cooperative model for architectural design', in *Knowledge-based Computer-Aided Architectural Design*, G.Carrara and Y.E. Kalay (eds.), Elsevier, pp.213-216, 1994.

[27] Reinschmidt, K. and G.A. Finn, 'Smarter computer-aided design', *IEEE Expert*, Vol.9, No.4, pp. 50-55, 1994.

[28] Harrison, S., 'Computing and the social nature of design', *ACADIA*, Vol.12, No.1, pp.10-18, 1993.

[29] Clayton,M et.al., 'Interpretation objects for multi-disciplinary design', in *Artificial Intelligence in Design '94*, *op. cit.*, pp. 573-590.

[30] Caneparo, L., 'Shared virtual reality for architectural design', in Proceedings of *CAAD futures 1997*, *op. cit.*, pp. 431-442.

[31] Bijl, A., *Computer Discipline and Design Practice: Shaping Our Future*, Edinburgh University Press, Edinburgh, pp. 172- 210, 1989.

Chapter
8

Conclusion

"...our use of computers now is a part of our existence and that our future is inexorably bound up in their further development. Computers as we now know them, and their current applications, do not define future computers. We have to decide what we want computers to be, while striving to realise our intentions, and we should expect to reshape our definitions... (A.Bijl. 1989, p.230)"

In this chapter, I summary the previous discussions and illuminate the main issues of this thesis: 'a design phenomenon of thinking-action' and 'mental space as design computational metaphor'. It includes some implications for CAAD, prospects, and further research plans.

CHAPTER 8: CONCLUSIONS

All architects do not have the abilities to design all kinds of buildings. The architect as a profession has become subdivided into various fields, such as an urban designer or an interior designer; even they become specialised as an office, school, or hospital designer. The architect is therefore only a specialist who has more experience and knowledge of its domain; at best, has a greater gift for graphicacy than laymen do. They can produce a design through intensive efforts, though some design ideas pop into from unexpected sources. Thus, it can be supposed that design results from the designer's accumulated knowledge, experience, or professional skills.

If the designer's knowledge and experience are explicated and if the mechanisms of the design processes are understood, design, even a creative design, can be formalised as design methods or programmed into computers. Many design studies have committed to these works. However, even though some design activities can be explained in terms of knowledge or cognition, little of them could so far be systematised by design methods or implemented by computers, except for some quantitative design problems.

During this research, I have been haunted by a question whether computers can generate actual designs. To answer this problem, I have inquired what designing is, and how computers are used for the designer in first two chapters.

Through the literature reviews, in chapter 2, I identify three design models for the design studies within the problem solving or information processing paradigm: systematic three-step design models; heuristic knowledge models; and cognitive models.

In chapter 3, I have analysed the applications of computers for architectural design and classify them into three categories: computers as a design information system; computers as a graphical medium; and computers as a solution-generating tool. Through this study, I recognise two distinctive tendencies in the development of CAAD - the direction towards intelligent systems and towards design graphic tools, and then describe the back and forth shifts in CAAD research concerns between these two directions during the past 40 years.

Despite the development of AI and computer science, it is the case that the application of computers in practical designing, especially the early design stage, remains in its beginning. This recognition has led CAAD research to focus to seek new directions such as man-machine symbiosis systems; integrated design systems; or to search for a solution from the advanced computational technologies or a new paradigm for computerising design. This thesis belongs to the last category – that is, it aims to establish a new theoretical framework for the computation of architectural design.

Accordingly, this thesis starts with a doubt about whether design is a problem-solving activity in the information-processing mechanism. This sharing paradigm between the research fields related to computing has been still prevailing in CAAD research. Throughout this thesis, I have argued that this paradigm is alien to the design domain, especially architectural design. I contend that design is not simply a search process, decision-making, or knowledge-based activity. Design is not geared only to solve problems but also to make something useful. Moreover, design activity is involved not only in reasoning, intellectual efforts or knowledge but also in intuition, creativity and imagery. The nature of subjective perception cannot be defined in entirely objective formulations of a design problem, and hence it is not computable, at least, by the current computational techniques.

This is a significant necessity to establish a designerly approach for a mediating design model or computational model, which can furnish the distinctive natures of designing that include a methodological and artistic constitution. Even if this designerly approach may not be accepted by the rationalistic viewers or may not be immediately implemented within today computer techniques, we need, at least, to establish a theoretical framework for computers as a design tool that has no appropriate computational paradigm yet.

From this observation, in chapter 4, I criticise the problem-solving paradigm in the design domain, in regards of the wickedness of design problems; the limitations in problem-solving design process; the shortcomings in the cognitive models; and the failure of computers as a problem-solver. These reviews lead me to set up a design model as a phenomenon of design *thinking-action*. It, alongside a mental model – mental space, are the main themes in this thesis.

Design as a Phenomenon of Thinking-Action

This thesis has argued that design thinking/action is a common phenomenon occurring in designing, and it takes place in the designer's mental space. Design thinking is regarded as the mental activities in forming design concepts or generating images, in which the designer interprets and perceives a situation, basing on knowledge, experience, or inherited artistic gifts. It includes recognising a design problem, understanding a situation, reasoning and learning; and is often classified as a dual structure such as intuitive/rational thinking or propositional/pictorial mode.

But, it is impossible to segregate, by these dichotomies, all mental-activities that contribute to design thinking and action. Thus, design thinking should be regarded as an inclusive process as a whole rather than as the combination of disparate processes.

Any design action comes from a complex thinking process. The designer obscurely represents design ideas in the mind, and these ideas or images are visualised, exercised and developed by design actions – mainly by drawing. Here, design actions are a crucial medium for all of the design processes, that is, in analysing design problems, in studying forms, in memorising images, or in communicating design ideas with himself/herself, clients, or project participants.

Moreover, the most significant phenomenon in designing is that the two activities, doing the thinking and design action, usually occur and develop simultaneously. That is, as thinking, the designer is drawing. Thus, thinking and design action do not function separately but are complementary, in that designers do work through conscious thinking processes, and they learn and discover new facts and new forms through drawings. This is a design thinking-action phenomenon in designing.

This argument comes not only from theoretical reviews but also from the introspective observations of many drawings and notes that some architects produced in the early design stage.

In chapter 4, I also draw the salient features in design thinking-action differentiating from other problem-solving activities. Firstly, design is a creative activity. Here, creativity refers not an artistic mystique but a hard work to create something new, requiring 'persistence, resoluteness, and commitment[1]'. Thus, creativity is a self-conscious activity, involving design knowledge, experience, or professional skills.

Secondly, I observe that architects directly present ideas or images without interpreting into verbal thinking; that is, they are non-linguistic thinkers, but visual thinkers. Visual thinking contributes the designer to imagining in the mind about how the design might be, and to visualising the images into reality. In addition, visual thinking allows seeing the holistic interactions of design objects that may be lost when it is broken down into elements. Thus, it is the most designerly mode of all activities engaged in design thinking-action.

This design model may have particular implications for CAAD, for instance:

(1) Due to the variability and subjectivity of design activities, computer cannot (or will not) think and solve most of the high-level design problems, and thus the design process cannot be automated by a design system. That is, computers cannot be employed as a thinking-machine or problem-solver in CAAD, but can be used one of the design tools for the design activities occurring in thinking-action, such as by drawing fast, by supporting decisions, or by motivating the designer's creative potential.

(2) This design model posits the architect as a typical non-linguistic thinker. The architect transfers the imagined objects into physically realisable configurations by engaging in visual thinking and drawing. The mental operations involving in visualising graphically may have different structures, properties and functions of mechanism from those of conceiving verbally. It cannot be explained by traditional cognitive theories or in the problem-solving paradigm, which have ignored or undervalued the non-verbal cognition.

Thus, this design model requires a new theoretical framework that can provide the computational environment for enhancing design thinking-action. This impulse encourages me to examine the mental operations occurred in the design thinking-action phenomenon and to suggest a computational model for architectural design.

Mental Space Theory

The inquiry on mental space springs from the following motivation: CAAD research has felt the needs of understanding design activities, but little attention was paid to the actual mechanism of the design mental process that could provide an underlying theoretical ground for the computation of designing. In doing so, this theory analogises the designer's mind as what is the spatial element (as mental space) where design thinking-action takes place in.

I think of mental space as a conscious system in the designer's mind, which has its structures and functions that can transfer external events into inner symbolic representations (design thinking) and simultaneously visualise these internal representations into external process (design action). Thus, this theory analyses the designer's mental mechanisms into the memory system, mental space and interface between them. From this study, I recognise the important roles of mental space in the design process rather than that of memory system that has been the main concerns in the problem-solving or cognition fields.

I continue to inquire what the mental space functions in design process in chapter 5; what components it constitutes of and what affects on the designer's mental process in chapter 6. Firstly, I suggest the mental operations in mental space: generating design ideas; designing in mental space; visualising mental images. During the study of the design mental operations, I justify that designing is much more involved in self-conscious mental activities, and identify the functions of mental space as follows:

(1) a transitional realm that links between inner thinking and outward expression,
(2) a medium that transfers external events or objects into the various symbols (internal representation) and re-transfers from internal representation into external process (external visualisation), and
(3) a forum accommodating design thinking and design action at the same time and at the same place.

These operations are performed independently of the memory system; rather they are much influenced by the interface system that is defined in the thesis as the designer's attention or value system and that will almost certainly remain in the human territory until the far future.

Secondly, it is observed that the designer continuously represents, experiments design ideas and images in the virtual world, this process involving symbolic expressions. This theory suggests three kinds of the abstracted constituents that represent or operate on information in mental space: objects, relationships and events. Objects symbolise the physical elements of design with their properties, such as name, location, form, and movement; relationships link between objects or their properties; and events represent a design experience with a specific context. Among them, objects are the most important visual elements in mental space, which will be designed and developed into a design. In this process, information about events and relationships support the designer to generate and evolve designs in each different way.

The third inquiry is done on the roles of design knowledge and imagery in mental space. Design knowledge helps the designer to generate some design solutions; to make better decision; and to validate design conjectures. Paralleled with knowledge, imagery contributes to generating design ideas and manipulating them in mental space. In this thesis, imagery is defined as the designer's faculties that can produce and manipulate mental images.

More significantly, this thesis has suggested that imagery in the design process (1) can serve for reasoning and design problem-solving through mental synthesis and mental modelling; (2) can be used as a incentive that activates the designer's intuition and imaginations to achieve a creative design; and (3) can trigger the mental interaction between intuition and intellect. That is, imagery can function for connecting intuition and intellect that are equally valuable, indispensable for the design thinking process. Thus, this thesis posits imagery as the most important agency for creative, visual thinking and to harmonise knowing and imagination.

From these observations, I draw out some implications for the computation of designing:

(1) CAAD research has tried to develop formal models of the computational procedures that are likely to be carried out by information-processing mechanisms in the design process. Consequently, these mechanisms are defined by the precise manner in which they are encoded in memory and used to process information. However, designing cannot be structured in such a memory system, because designing is not a memory-based activity but depends mainly on the mental operations of mental space. As a result, to develop a computer system, CAAD research should understand the designer's mental process

involved in design thinking-action; and should pay more attentions to mental space than to the memory system.

(2) This thesis also identifies that computers cannot solve design problems but can only support the designer as a design tool. This awareness has led the focus of CAAD to shift from the computability of design to the usefulness of computer for design. This usefulness depends on how properly computers provide the computational environments that can support a wide range of the designer's thinking-action. In this context, mental space theory may provide CAAD research with rich implications, because this theory includes visual thinking, imagery, and drawing in which the designer is much more involved during the design process, in addition to verbal thinking, knowledge and problem-solving. Furthermore, the argument of the role of knowledge and imagery in mental space may give CAAD research valuable information on how the man-machine interface allocates the function of human and computers. That is, the mental space approach aims at a computer-based design environment that can maximise the potential of human imagery and the capability of computer's memory.

(3) I have shown in the thesis that creativity can be achieved by the exercise of imagination[2] or through experience of trial and error, and hence it can be enhanced potentially by the aid of computers. This argument indicates that the appropriate role of computer in the design domain is to provide an environment to motivate and enhance the designer's potential of creativity. For the computer to do so, it furnishes a computational environment in which the designer can create, represent and examine freely new design ideas and images, and can perform the design process more fast, safely and smoothly by applying the increasing computational technologies. In such an environment, computers can augment the designer's knowledge and imagery; can stretch the extent of mental space; and can be employed for a better design or more creative design.

Mental Space Computational Model (MSCM)

This thesis aims not only to suggest a new approach to understanding designing, but also to provide new insights of the potential roles of computers for architectural design. Thus, another reason that this thesis employs the spatial metaphor of the designer's mind is that it may provide the significant crux to transfer the objects, events and their interactions created in mental space into a computer environment. Consequently, in chapter 7, I examine the feasibility of mental space as a computational metaphor and suggest the mental space approach to CAAD.

The mental space computational model (MSCM) refers to a design computational environment to attempt to mimic the various mental performances and processes occurring in the architect's mental space. It consists of a design platform, prescriptive reference tools, and design visualising tools. This thesis also demonstrates the computation of the components of mental space: that is, objects being designed; operational knowledge about relationship between objects; and events linking between objects and context.

Instead of presenting a prototype computer system, this thesis explores the existing visualising tools, reference tools and integrated systems. These case studies may help to understand the gaps between the hypothesized mental space model and the computational environment of the existing or on-going research CAD applications for the early design stage, and may provide CAAD research with some insights of the mental space approach. That is, the deeper observations of the mental processes in mental space will lead CAAD to accommodating the designer's thinking and activities more appropriately, and its computational environment will be more acceptable to the designer.

Prospects and Further Research

This work began with a hypothesis that design thinking-action take place in the designer's mental space. Developing this research led to the first ideas of mental space becoming clear. I believe that the mental space theory can be a feasible theoretical framework for computerising architectural design. Even though I did not present a complete mental space design system that can implement all of its proposals, this theory can contribute to understanding the designer's mental processes occurring in design thinking/action, and it can provide comprehensive theoretical backgrounds for CAAD. Thus, it could be a new approach to developing the future design systems.

Moreover, its theoretical advantage is that this thesis has tried to avoid the dualistic arguments that are divided between artistic and scientific stands in the viewpoint of designing. It aims to account for some of the more mysterious design phenomena like imagery, imagination, or intuition, which have been overlooked by the design studies or CAAD research but play crucial roles in designing. As a result, this theory can be applied as a theoretical ground not only for the computation of designing but more broadly to design studies, design methodology, and architectural education.

However, this theory has not yet full-fledged; it should rather be understood as a stimulus for further discussion and examination. I also admit that it has some deficient aspects as an explicit theory, in that (1) many psychological hypotheses still remain in non-verified in the design research, even though some of them have been derived from the reports of cognitive psychology experiments; and (2) this thesis does not demonstrate a successful prototype system for proving the feasibility and utility of the mental space computational model. Accordingly, my future research will focus refining this theory by supplementing it with experimental evidence on the designer's mental operations, and I aim to work towards a mental space system by which mental space theory can be formulated and tested.

Reference

[1] Allinson, K., *The Wild Card of Design*, Butterworth Architecture, Oxford, pp. 189-196, 1993.

[2] Pateman, T., Key Concepts: A Guide to Aesthetics, Criticism and the Arts in Education, The Falmer Press, London, pp.33-35, 1991.

Appendix

- Appendix A: Bibliography
- Appendix B: Published Paper

Andre Brown and Hwa Ryong Lee, 'A Mental Space Model', *Cyber-Real Design: 5th International Conference on Computer in Architectural Design*, pp. 27-42, 1998.

Bibliography

Abecrombie, M.L.J., *The Anatomy of Judgement*, Basic Books, New York, 1960.

Achten, H., *Generic Representations*, Bouwkunde, Eindhoven, 1997.

Akin, Ö., *Psychology of Architectural Design*, Pion Limited, London, 1986.

Akin, Ö. and L. Chengtah, 'Design protocol data and novel design decisions', *Design Studies*, Vol.16, No.2, pp. 211-236, 1995.

Alberto Pérez-Gómez, *Architecture and the Crisis of Modern Science,* The MIT Press, Cambridge, 1984.

Alexander, C., *Notes on the Synthesis of Form*, Harvard University Press, Cambridge, 1964.

Alexander, C. and B. Poyner, 'The atoms of environmental structure', in *Developments in Design Methodology,* N. Cross (ed.), Wiley, Chichester, pp.123-133, 1984.

Allemang, D., 'Combining case-based reasoning and task-specific architectures', *IEEE EXPERT*, Vol.9, No.5, pp. 24-33, 1994.

Allinson, K., *The Wild Card of Design: A perspective on Architecture in a Project Management Environment*, Butterworth Architecture, Oxford, 1995.

Al-Sallel, K and L.O.Degelman, 'A hypermedia model for supporting energy design in buildings', *ACADIA*, 1994.

Amstrong, D.M., 'Early causal and Functionalist Views (1981)', in *Mind and Cognition,* W.G.Lycan (ed.), Blackwell Publishers, Oxford, 1994.

Amstrong, D.M., 'Early Causal and Functionalist Views', in *Mind and Cognition,* W.G. Lycan (ed.), Blackwell Publishers, Oxford, 1990.

Anderson, J.R., 'Arguments concerning mental imagery', *Psychological Review,* No. 85, pp. 249-277, 1978.

Anderson, J.R., *The Architecture of Cognition*, Harvard University Press Cambridge, 1983.

Anderson, R.L., *Art in Small-Scale Societies*, Prentice-Hall, Englewood Cliffs, 1989.

Aoki, Y., 'An association model for a CAD system', in Artificial Intelligence in design '94, J.Gero and F.Sudweeks (eds.), Kluwer Academic Publishers, pp.219-236, 1994.

Archer, L.B., 'The structure of the design process', in *Design Methods in Architecture,* G. Broadbent and A. Ward (eds.), Lund Humphries Publishers Limited, pp. 76-102, 1969.

Archer, L.B., 'The Three Rs', *Design Studies,* Vol. 1 No. 1, July, pp18-20, 1979.

Archer, L.B., 'Whatever become of design methodology?', *Design Studies,* Vol. 1, No.1, pp. 17-18, 1979.

Archer, L. B., 'Systematic method for designers', in *Development in design methodology*, N. Cross (ed.), Wiley, New York, pp. 57-82,1984.

Arnheim, R., *New Essays on the Psychology of Art*, University of California Press, Berkeley, 1986.

Asimow, M., *Introduction to Design,* Prentice-Hall, Englewood Cliffs, New Jersey, 1962.

Bahrick, H.P and B. Boucher, 'Retention of visual and verbal codes of the same stimuli', *Journal of Experimental Psychology*, 78, pp. 417-422, 1968.

Balchin, W.G.V., 'Graphicacy', *Geography*, Vol.57, pp. 185-195, 1972.

Beach, L.R., *Image Theory: Decision-Making in Personal and Organisational Contexts*, John Wiley & Sons, Chichester, 1990.

Beach, L.R. and T.R. Mitchell, 'Image theory: A behavioural theory of decision making in organisations', *Research in Organisational Behaviour*, Vol. 12, pp.1-41, 1990.

Beheshti, R., 'Design decisions and uncertainty', *Design Studies*, Vol.14, No.1, 1993.

Bench-Capon T.J.M., *Knowledge Representation: An Approach to Architectural Intelligence*, Academic Press Limited, London, 1990.

Benton, T., 'Villa Savoye and the architect's practice', in *Drawings from the Le Corbusier Archive*, A. Tzonis (ed.), AD Edition, London, 1986.

Best, G., 'Method and intention in architectural design', in *Design methods in Architecture*, G. Broadbent and A. Ward (ed.), Lund Humphries Publishers, pp.147-165, 1969.

Beveridge, M. and Pakins, E., 'Visual representation in analogue problem solving, *Memory and Cognition*, No. 15, pp. 115-147, 1987.

Bhatta S., A. Goel and S. Prabhakar, 'Innovation in analogical design: a model-based approach', in *Artificial Intelligence in Design '94*, J. Gero and F. Sudweeks (eds.), Kluwer Academic Press, Dordrecht, the Netherlands, 1994.

Bijl, A., *Computer Discipline and Design Practice: Shaping Our Future*, Edinburgh University Press, Edinburgh, 1989.

Bijl, A, 'On knowing—feeling and expression', in *CAAD Futures '91*, G.N. Schmitt (ed.), Vieweg, Wiesbaden, pp. 157- 176, 1992.

Blackburn, S., *The Oxford Dictionary of Philosophy*, Oxford University Press, Oxford, 1996.

Block, N., 'Introduction: What is the issue', *Imagery*, N.Block (ed.), The MIT Press, Cambridge, 1981.

Block, N., 'Mental pictures and cognitive science', *Philosophical Review 83*, pp. 499-542, 1983.

Bonnet, A., J.P. Halton and J.M. Truong, *Expert Systems*, translated by J.Howlett, Presntice Hall, New York, 1988.

Boulding, K.E, *The Image*, The University of Michigan Press (3rd Press), 1975.

Bourne, L., R. Dominowski and E. Loftus, *Cognitive Processes*, Prentice-Hall, NJ, 1979.

Bradshaw, J.L. and N.C. Nettleton, *Human Cerebral Asymmetry*, Prentice Hall, 1983.

Broadbent, G., *Design in Architecture: Architecture and the Human Science*, David Fulton Publishers, London, 1988 (revised).

Brooks, C. and R.P. Warren, *Modern Rhetoric* (2nd ed.), Harcout Brace & world, New York, 1958.

Brown, A.G.P and F. Horton, 'Computer aids for design development', in *Computers in Architecture Tools for Design*, F. Penz (ed.), Longman, Essex, pp. 15-24, 1992.

Brown, A.G.P., M. Knight, F. Corenen and P. Geraghty, 'Representation and reasoning in architectural space: a linear tesseral approach', *Proceedings of ECAADE 1997*, T.V.Wien, Viennd, September 1997.

Burnett, C., 'The architects access to information: constraints on the architect's capacity to seek, obtain, translate and apply information', in *National Bureau of Standards GCR*, pp. 78-153, 1979.

Caneparo, L., 'Shared virtual reality for architectural design', in *Proceedings of CAAD Futures 1997*, R. Junge (ed.), Kluwer Academic Publishers, Dordrecht, pp. 431-442, 1997.

Carrara, G. and Y.E. Kalay, 'preface', in *Knowledge-Based Computer Computer-aided Architectural Design*, G. Carrara and Y. Kalay (eds.), Elsevier, Amsterdam,1994.

Carrara G., Y.E. Kalay and G. Novembri, 'Knowledge-based computational support for architectural design', in *ACADIA 1994*, 1994.Carrara, G., Y.E. Kalay and G. Novembri, 'Knowledge-based computational support for architectural design, *Automation in Construction*, 3, 1994.

Carrington, J., 'Re-engineering AutoCAD', *CAD User*, November, 1995.

Ceaik, K.J.W., *The Nature of Explanation*, Cambridge University Press, Cambridge, England, 1943.

Chan, C.S., 'Cognitive processes in architectural design problem solving', *Design Studies*, Vol.11, No.2, pp. 60-79, 1990.

Chandrasekaran, B., 'Design problem solving: a task analysis', *AI Magazine*, pp. 59-71, winter 1990.

Churchman, C.W., *Prediction and Optimal Decision*, Printice-Hall, Englwood Cliffs, N.J., 1962.

Clayton, M. *et. al.*, 'Interpretation objects for multi-disciplinary design', in *Artificial Intelligence in Design '94*, J.S. Gero and F. Sudweeks (eds.), Kluwer Academic Publishers, pp. 573-590, 1994.

Conklin, J., 'Hypertext: An introduction and survey', *Computer*, Vol.20, pp. 17- 42, 1987.

Cornik, S.M., 'HyperCode: The building code as a Hyperdocument', *Engineering with Computer*, Vol.7, No.1, pp. 37- 46, 1991.

Cotton, B. and R. Oliver, *Understanding Hypermedia*, Phaidon Press Ltd., London, 1994.

Coyne, R. and A. Snodgrass, 'Is designing mysterious? Challenging the dual knowledge thesis', *Design Studies*, Vol.12 No.3, pp. 124-131, 1991.

Coyne, R. and A. Snodgrass, 'Rescuring CAD from rationalism', *Design Studies*, Vol.14, No.2, pp. 100-123, 1993.

Coyne, R.F. and E. Subrahmanian, 'Computer supported creative design: a pragmatic approach', in *Modelling Creativity and Knowledge-Based Creative Design*, J.S. Gero and M.L. Maher (eds.), Lawrence Eribaum Associates, pp. 295- 304, 1993.

Crosley, M.L., *The Architect's Guide to Computer-Aided Design*, John Wiley & Son, New York, p. 138, 1988.

Cross, N., *The Automated Architect*, Pion Limited, London, 1977.

Cross, N., 'Design method and scientific method', in *Design: Science: Method*, R. Jacques and J.A. Powell (eds.), Westbury House, pp.18-29, 1981.

Cross, N., J. Naugton and D. Walker, 'Design method and scientific method', *Design Studies*, Vol. 2 No. 4, pp. 195-201, 1981.

Cross, N., 'Designerly ways of knowing', *Design Studies*, Vol. 3 No. 4, 1982.

Cross, N., 'Introduction' and 'The management of design process', in *Developments in Design Methodology*, N. Cross (ed.), John Wiley & Son Ltd., 1984.

Cross, N., 'Research in design thinking', in *Research in Design Thinking: Proceedings of Workshop*, Delft University Press, 1991.

Curtis, W.J.R., *Le Corbusier Ideas and Forms* (2nd ed.), Phaidon Press Ltd., London, 1992.

Daley, J., 'Design creativity and the understanding of objects', *Design Studies,* Vol.3 No.3, 1982.

Dasgupta, S., 'Herbert Simon's '*Science of Design*': Two decades later', in *First International Conference on Intelligent Systems Engineering*, Heriot-Watt University, Edinburgh, 1992.

Dasgupta, S. *Creativity in Invention and Design,* Cambridge University Press, 1994.

David, G. and M. Olson, *Management Information System: Conceptual Foundations, Structure and Development,* McGraw-Hill (2nd ed.), 1985.

Day, M., 'Draftsman's contract', *Personal Computer Magazine,* July 1994.

de Bono, E., *Parallel Thinking,* Penguin Books, London, pp. 187-194, 1994.

Denis, M., *Image and Cognition,* Harvester, New York, 1991.

Dennet, D.C., 'The nature of images and the introspective trap', in *Imagery,* N.Block (ed.), The MIT Press, Cambridge, 1981.

Descartes, R., *Discourse on Method and the Meditations,* Penguin, Middlesex, 1968.

Dilnot, C., 'Transcending science and 'anti-science' in the philosophy of design method', in *Design : Science: Method,* R. Jacques, and J.A. Powell, (eds.), Westbury House, 1981.

Dixon, J.R., 'On research methodology towards a scientific theory of engineering design', in *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AI EDAM),* Vol.1 No.3, 1988.

Do, E.Y., 'What is in a diagram that a computer should understand?', in *Proceeding CAAD Futures 1995*, M. Tan and R. The (eds.), National University of Singapore, pp. 469-480, 1995.

Do, E.Y., 'Computability of design diagram', in *Proceedings of CAAD Futures 1997,* R. Junge (ed.), Kluwer Academic Publishers, Dordrecht, pp. 163-170, 1997.

Domeshek, E.A. and J.L. Kolodner, 'Case-based design aid for architecture', in *Artificial Intelligence in Design '92,* J.S.Gero (ed.), Kluwer Academic Publishers, Dordrecht, pp. 497- 515, 1992.

Dryfus, H.L., *What Computers Can't Do: The Limits of Artificial Intelligence*, Harper and Row, New York, 1972.

Dryfus, H.L., *Being-in-the-World: A Commentary on Heidegger's Being and Time*, MIT Press, Cambridge, 1991.

Dryfus, H.L., *What Computers still Can't Do,* MIT Press, Cambridge, MA, 1993.

Eastman, C, 'Explorations of the cognitive processes in design', in *Department of Computer Science Report,* Carnegie Mellon University, Pittsburgh, 1968.

Eastman, C.M., 'Information and databases in design', *Design Studies*, Vol.1, No.3, 1980.

Eastman, C.M., 'A data model for design knowledge', in *Knowledge-Based Computer-Aided Architectural Design,* G. Carrara and Y. E. Kalay (eds.), Elsevire, Amsterdam, pp. 95- 122, 1994.

Eder, W.E., 'Engineering design—art, science and relationships', *Design Studies*, Vol.16, No.1, pp. 117- 127, 1995.

Edwards, W.B., *Understanding Architecture through Drawing*, E & FN Spon, London, 1994.

Eekels, J. and N.F.M. Roozenburg, 'A methodological comparison of the structures of scientific research and engineering design: their similarities and differences', *Design Studies,* Vol.12, No.4, 1991.

Engelmore, R. and T. Morgan, *Blackboard System*, Addison-Welsey, New York, 1989.

Ernest, C.H., 'Imagery and memory in the blind: A review', in *Imagery and related mnemonic processes: Theories, individual differences, and applications*, M.A. McDaniel and M. Pressley (eds.), Springer-Verlag, New York, pp. 218-238, 1987.

Evans, R. and P. Russell, *The Creative Manager*, Unwin, 1989.

Evt, S.K., S. Khayyal and V.E. Sanvido, 'Representing building product information using Hypermedia', *Journal of Computing in Civil Engineering,* Vol.6, No.1, pp. 3-18, 1992.

Farah, M.J., 'The neurological basis of mental imagery: a componential analysis', in *Visual Cognition*, S. Pinker (ed.), MIT Press, Cambridge, 1986.

Fawcett, W., 'A note on the logic of design', in *Design Studies*, Vol.8, No.2, 1987.

Finke, R.A, *Creative imagery: Discoveries and Inventions in Visualisation*, Erlbraum, Hillsdale, NJ, 1990.

Finke, R.A., *Principles of Mental Imagery*, The MIT Press, Cambridge, 1989.

Fisher, D.H., *Historian's Fallacies: Toward a Logic of Historical Thought,* Harper & Row, New York, 1970.

Flemming, U., 'More than the sum of the parts: the grammar of Queen Anne', in *Planning and Design,* Vol. 14, No. 3, pp. 323- 350, 1986.

Flemming, U., R.F. Coyne, and R. Woodbury, 'SEED: A software environment to support the early phases in building design', in *ARECDAO 93: Proceeding International Conference on Computer Aided Design in Architecture and Civil Engineering,* Barcelona, Spain, pp. 111-122, 1993.

Flemming, U., 'Artificial intelligence and design: a mid-term review', in *Knowledge-Based Computer-Aided Architectural design,* G. Carrara and Y. E. Kalay (eds.), Elsevier, Amsterdam, 1994.

Fodor, J.A., 'Imagistic representation', in *Imagery,* N. Block (ed.), The MIT Press, Cambridge, 1981.

Franz, J. M., 'A critical framework for methodological research in architecture', in *Design Studies,* Vol. 15 No. 4, 1994.

Galle, P. and L.B. Kovács, , 'Introspective observations of sketch design', in *Design Studies,* Vol.13, No.3, pp. 229-272, 1992.

Gelerner, M., *Sources of Architectural Form: A Critical History of Western Design Theory,* Manchester University Press, Manchester and New York, 1995.

Gero, J. and M. Maher, 'Future roles of knowledge-based systems in the design process', in *CAAD Futures '87*, T. Maver and H. Wagter (eds.), Elsevier, 1987.

Gero, J.S., 'Prototypes: a new schema for knowledge-based design', *Working Paper,* Architectural Computing Unit, Department of Architectural Science, University of Sydney, 1987.

Gero, J.S., 'Design prototypes: A knowledge representation schema for design, *AI Magazine 11 (4)*, pp. 26- 36, winter, 1990.

Gero, J.S., 'What are we learning from designers and its role in future CAAD tool', in *Proceedings of CAAD Futures '97*, R. Junge (ed.), Kluwer Academic Publishers, Dordrecht, 1997.

Giarratano, J. and G. Riley, *Expert System: Principles and Programming,* PWS-KENT Publishing Company, Boston, 1989.

Goel, V. and P. Pirolli, 'Design within information-processing theory: the design problem space, *AI Magazine*, spring, 1989.

Goel, A. et al., 'A Cross-Domain Experiment in Case-Based Design support: ArchieTutor', in *Case-Based Reasoning: Papers from the 1993 Workshop*, AAAI Press, California, 1993.

Gordon, W.J.J., *Synetics: the Development of Creative Capacity*, Harper & Brothers, New York, 1961.

Grant, D., 'Aims and potentials of design methodology', *Design method and Theories*, Vol.20, No.1, pp. 389-394, 1986.

Greence, J., *Memory, thinking and Language: Topics in Cognitive Psychology,* Methuen, London, 1987.

Gregory, S.A., *The Design Method,* Butterworth, London, 1967.

Groák, S., *The Idea of Building: Thought and Action in the Design and Production of Buildings*, E & FN Spon, London, 1992.

Gross M.D., C. Zimring and E. Do, "Using Diagrams to Access a Case Base of Architectural Designs," in *Artificial Intelligence in Design '94,* J. Gero and F. Sudweeks (eds.), Kluwer Academic Press, Dordrecht, the Netherlands, pp.129-144, 1994.

Gross, M.D., 'The fat pencil, the cocktail napkin, and the slide library', in Proceedings of *ACADIA 1994*, A. Harfmann and M. Fraser (eds.), pp. 103-112, 1994.

Hadamard, J., *Psychology of Invention in the Mathematical Field*, Princeton University Press, Princeton, N.J., 1954.

Harfmann, A., 'The rationalising of design', in *Computability of Design*, Y. Kalay (ed.), John Wiley & Sons, New York, 1987.

Harrison, S., 'Computing and the social nature of design', *ACADIA*, Vol.12, No.1, pp.10-18, 1993.

Hawkes, D., 'The technical imagination: thoughts on the relation of technique and design in architecture', *The Journal of Architecture*, Vol.1, winter, pp. 335-346, 1996.

Heimsath, C., *Behavioural Architecture,* McGraw-Hill Book Company, New York, 1977.

Hillier, B., J. Musgrove and P. O'Sullivan, 'knowledge and Design', in Developments in Design Methodology, N. Cross (ed.), John Wiley & Sons, Chichester, 1984.

Hyde, R., 'Design procedures in architectural design applications in CAAD', *Design Studies,* Vol.10, No.4, 1989.

Isaacson, R.L. and M.L. Hutt, *Psychology: the Science of Behaviour,* Harper & Row, Publishers (2nd ed.), New York, 1972.

Jansson, D.G. and S.M. Smith, 'Design Fixation', *Design Studies,* Vol.12, No.1, 1991.

Johnson-Laird, P.N., *Mental Models*, Cambridge University Press, Cambridge, 1983.

Jonas, W., 'Design as problem-solving? or: here is the solution—what was the problem?', *Design Studies,* Vol.14, No.2, pp. 157-170, 1993.

Jones, J.C., 'A method of systematic design', in *Conference on Design Methods,* J.C. Jones and D. Thornley (eds.), Pergamon, Oxford, 1963.

Jones, J.C., 'The state-of-the -art in design methods', in *Design Methods in Architecture,* G. Broadbent and A. Ward (eds.), Lund Humphries Publishers Limited, 1969.

Jones, J.C., 'How my thoughts about design methods have changed during the years', *Design Method and Theories,* Vol,11, No.1, pp. 50-62, 1977.

Jones, J.C., 'Designing Designing', *Design Studies,* Vol.1, No.1, pp. 31-35, 1979.

Kahney, H., *Problem Solving: A Cognitive Approach,* Open University Press, Milton Keynes, 1986.

Kalary, Y.E., 'Editorial', *Automation in Construction,* 3, 1994.

Kaufmann, G., 'Imagery effects on problem solving', in *Imagery: Current Developments,* Routledge, London, P. Hampson, D. Marks and J. Richardson (eds.), 1990.

Koestler, A., *The Act of Creation,* Macmillan, New York, 1994.

Kolodner, J., *Case-*Based *Reasoning,* Morgan Kaufmann Publishers, Inc., San Mateo, 1993.

Kosslyn, S.M., 'Scanning visual images: some structural implications', *Perception and Psychophysics,* 14, pp. 90-94, 1973.

Kosslyn, S.M., *Image and Mind,* Harvard University Press, Cambridge, 1980.

Kosslyn, S.M., *Image and Brain: The Resolution of the Imagery Debate,* The MIT Press, Cambridge, 1994.

Kossyln, S.M., T.M. Ball and B.J. Reiser, 'Visual images preserve metric spatial information evidence form studies of image scanning', *Journal of Experimental Psychology,* 4, pp. 47-60, 1978.

Kosslyn, S.M., S. Pinker, G. Smith and S. Shwarz, 'On the demystification of mental imagery', in *Imagery,* N. Block (ed.), The MIT Press, Cambridge, pp. 131-150, 1981.

Kurmann, D., N. Elte and M. Engeli, 'Real-time modelling with architectural space', in Proceedings of *CAAD futures 1997,* R. Junge (ed.), Kluwer Academic Publishers, pp. 809-819, 1997.

Larson, M.S., *Behind the Post-modern Facade: Architectural Change in Late Twentieth-Century America,* University of California Press, Berkeley, 1995

Laudon, K. and J.P. Laudon, *Essentials of Management Information Systems: Organisation and Technology,* Prentice-Hall International, Inc., NJ, 1995.

Lawrence, R.J, 'Architectural design tools: simulation, communication and egociation', *Design Studies,* Vol.14, No. 3, 1993.

Lawson, B., 'Cognitive strategies in architectural design', *Ergonomics,* Vol.22, No.1, pp. 59-68, 1979.

Lawson, B., *How Designers Think,* Butterworth Architecture, London, 1988.

Lawson, B., *How Designers Think* (2nd ed.), Butterworth Architecture, Oxford, 1990.

Lawson, B., 'The art of the process', in *The Art of The Process: Architectural design in practice,* RIBA, London, 1993.

Lawson, B., *Design in Mind,* Butterworth-Heinemann Ltd, Oxford, 1994.

Lawson, B. and P. Scott, 'Can concurrent verbalisation reveal design cognition?', *Design Studies,* Vol.16, No.2, pp. 237- 259, 1995.

Lera, S., 'At the point of decision', *Building,* May, pp. 47-48, 1982.

Levin, P.H., 'Decision-making in urban design', in *Developments in Design Methodology,* N. Cross (ed.), Wiley, Chichester, 1984.

Logan B. and T. Smithers, 'Creativity and Design as Exploration', in *Modelling Creativity and Knowledge-Based Creative Design,* J. S. Gero and M. L. Maher (eds.), Lawrence Erlbaum Assocates, Inc., New Jersey, pp. 139-175, 1993.

Logie, R.H., 'Visuo-Spatial Short-term memory: visual working memory or visual buffer?', in *Imagery and Cognition,* C. Cornoldi and M.A. McDaniel (eds.), Springer-Verlag, New York, pp. 77-94, 1991.

Losee, J., *A Historical Introduction to the Philosophy of Science* (2nd ed.), Oxford University Press, Oxford, pp. 114-130, 1980.

Luckman, J., 'An approach to the management of design', in *Developments in Design Methodology,* N. Cross (ed.), John Wiley & Sons, Chichester, pp.83-105, 1984.

Lycan, W.G., *Mind and Cognition: A reader,* Blackwell, Oxford, 1994.

Maher, M.L., F. Zhao and J.S. Gero, 'A knowledge-based model for creative design, *Proceedings of NSF Engineering Design Research Conference,* University of Massachusetts, pp. 333-346, 1989.

Maher, M.L., and F. Zhao, 'Dynamic associations for creative Engineering design', in *Modelling Creativity and Knowledge-Based Creative Design,* J.S. Gero and M.L. Maher (eds.), Lawrence Erlbaum Associates, NJ, pp. 329-351, 1993.

March, L.J., 'The logic of design', in *Developments in design methodology,* N. Cross (ed.), Wiley& Sons, Chichester, New York, 1984.

Marks, D.F., 'On the relationship between imagery, body and mind', in *Imagery,* Routledge, London, 1990.

Markus, T.A., 'The role of building performance measurement and appraisal in design method', *The Architect's Journal,* pp. 1567- 1573, Dec. 1967.

Marr, D., *Vision,* W.H. Freeman, San Francisco, 1982.

Mayer, R.E., *Thinking, Problem Solving, Cognitive,* W.H. Freeman and Company, New York, 1983.

McCall, R.J., 'MIKROPLIS: a Hypertext system for design', *Design Studies,* Vol. 10, No. 4, pp. 228-237, 1989.

McCall, R., E. Johson and M. Smith, 'HyperSketching: Design as creating a graphic hyperdocument', in Proceeding of *CAAD futures 1997,* R. Junge (ed.), Kluwer Academic Publishers, pp.849-854, 1997.

McDermott, J., 'Domain knowledge and the design process', *Design Studies,* Vol.3 No.1, 1982.

McKim, R.H., *Thinking Visually: A Strategy Manual for Problem Solving,* Wadsworth, 1980.

Miller, G.A., E. Galanter, and K. Pribram, *Plans and the Structure of Behaviour,* Henry Holt, New York, 1960.

Mitchell, W.J., *Computer-Aided Architectural Design,* Petrocelli/Charter, New York, 1977.

Mitchell, W.J., 'Three Paradigms for Computer-Aided Design', in *Knowledge-Based Computer-Aided Architectural Design,* G. Carrara and Y.E. Kalay (ed.), Elsevier, pp. 379-388, 1994.

Mitchell, W.J., *The Logic of Architecture,* MIT Press, Cambridge, 1990.

Mole, A., *Information Theory and Esthetic Perception*, translated by J. E. Cohen, University of Illinois Press, Urbana and London, 1966.

Morris, P.E. and P.J. Hampson, *Imagery and Consciousness*, Academic Press, London, 1983.

Mounoud, P., 'The ontogenesis of different types of thought: language and motor behaviours as non-specific manifestations', in *Thought without Language*, L. Weiskrantz (ed.), Oxford Science Publications, New York, 1988.

Murthy, S.S. and S. Addanki, 'PROMPT: An innovative design tool', in *Proceedings of AAAI sixth National Conference on Artificial Intelligence,* Seattle, pp. 637- 642, 1987.

Newell A, 'Limitations of the current stock of ideas about problem-solving', in *Electronic Information Handling,* A. Kent and O. Taulbee (eds.), Spartan Books, Washington, DC, pp. 195-207, 1965.

Newell, A., 'On the analysis of human problem solving Protocols', *in Calculet Fornalisation dans les Sciences design L'Homme*, J.C. Garin and B. Jaulin (eds.), Paris, 1968.

Newell, A., 'Heuristic programming: ill-formed problems', in *Progress in Operations Research,* J. Aronofsky (ed.), Vol.3, Wiley, New York, 1969.

Newell, A. and H.A. Simon, *Human Problem Solving*, New York, Prentice Hall, pp. 72-73, 1972.

Norman, R.B., 'Intuitive design and computation', in *Computability of Design*, John Wiley & Son, New York, pp. 295-301, 1987.

Ócatháin, C.S., 'Why is design logically impossible?', *Design Studies,* Vol.3, No.3, 1982.

Oksala, T., 'Design intelligence: Evolutionary and cognitive aspects', *Automation in Construction* 3, 1994.

Oxman, R. and R.M. Oxman, 'Prior knowledge in design: a dynamic knowledge-based model of design and creativity', *Design Studies*, Vol. 11, No. 1, pp. 17-28, 1990.

Oxman, R. and R.M. Oxman, 'Refinement and adaptation in design cognition', *Design Studies*, Vol.13, No.2, pp. 117-133, 1992.

Oxman, R. and R.M. Oxman, 'PRECEDENTS: Memory structure in design case libraries', in *CAD Futures '93*, U. Flemming and S. Van Wyk (eds.), Elsevier, Amsterdam, pp. 273- 287, 1993.

Oxman, R. and R.M. Oxman, "Case-Based Design: Cognitive Models for Case Libraries," in *Knowledge-Based Computer-Aided Architectural Design,* G. Carrara and Y.E. Kalay (eds.), Elsevir, pp. 45- 67, 1994.

Oxman, R., 'Observing the observes: research issues in analysing design activity, *Design Studies*, Vol.16, No.2, pp. 275-283, 1995.

Oxman, R., 'Cognition and design', *Design Studies, Vol. 17, No.4, pp. 337-340, 1996.*

Paivio, A., *Imagery and Verbal Process,* Rinehart and Winston, New York, 1971.

Paivio, A., 'A theoretical analysis of the role of imagery in learning and memory', in *The Function and Nature of Imagery*, P. Sheehan (ed.), Academic Press, New York, pp.253-279, 1972.

Paivio, A., 'Perceptual comparisons through the mind's eye, *Memory and Cognition*, Vol.3, No.6, 1975.

Pateman, T., *Key Concepts; A Guide to Aesthetics, Criticism and the Arts in Education*, The Falmer Press, London, 1991.

Patterson, D. W., *Introduction to Artificial Intelligence and Expert Systems*, Prentice-Hall International, Inc., 1989.

Pauly, D., 'The Chapel of Ronchamp', in *Drawings from the Le Corbusier Archive*, A.Tzonis (ed.), AD Editions Ltd., London, 1986.

Penn, A. *et.al.*, *Pangea V2.1b: User's Guide*, UCL, 1997.

Pinker,S and S.M. Kosslyn, 'The representation and manipulation of three-dimensional space in mental images, *Journal of Mental Imagery*, 2, pp. 69-83, 1978.

Pinker, S., 'Visual cognition: Introduction', in *Visual Cognition*, S. Pinker (ed.), MIT Press, Cambridge, 1986.

Place, U.T., 'Is consciousness a brain process?', in *Mind and Cognition*, W.G. Lycan (ed.), Blackwell, Oxford, 1994.

Pohl, J. and L. Myers, 'A distributed co-operative model for architectural design', in *Knowledge-Based Computer-Aided Architectural Design*, G. Carrara and Y. Kalay (eds.), 1994.

Polanyi, M., 'Tacit Knowing: its bearing on some problems of philosophy', in *Review of Modern Physics*, Vol. 34, pp. 601-616, 1962.

Polya, G., *Mathematical Discovery (Vol.1)*, Wiley, New York, 1962.

Potter, N., *What Is a Designer: Things, Plan, Messages* (3rd ed.), Hyphen Press, London, 1989.

Purcell, A.T., Gero, J.S., H.M. Edwards and E. Matka, 'Design Fixation and intelligent design aids', in *Artificial Intelligence in Design '94*, J.S. Gero and F. Sudweeks (eds.), pp. 483-495, 1994.

Pylyshyn, Z.W., 'What the mind's eye tells the mind's brain: A critique of mental imagery, *Psychological Bulletin*, No. 80, pp 1-24, 1973.

Pylyshyn, Z., 'The imagery debate: Analog media versus tacit knowledge', in *Imagery*, N. Block (ed.), The MIT Press, Cambridge, p153-158, 1981.

R.I.B.A., *Handbook of Architectural Practice and Management*, RIBA, London, 1965.

Rapoport, A., 'Facts and models', in *Design methods in Architecture*, G. Broadbent and A. Ward (eds.), Lund Humphries Publishers, 1969.

Rata, R., *Hypertext: From Text to Expertext*, McGraw-Hill Book Company, London, 1991.

Reed, S.K., *Cognition: Theory and Applications* (4ed.), Brooks/Cole Publishing Company, Pacific Grove, 1996.

Reinschmidt, K. and G.A. Finn, 'Smarter computer-aided design', *IEEE Expert*, Vol.9, No.4, pp. 50-55, 1994.

Reitman, W.R., 'Heuristic decision procedures, open constraints, and the structure of ill-defined problems', in *Human Judgements and Optimality*, M. Shelly *et. al.* (eds.),Wiley, New York, 1964.

Richardson, J.T.E., *Mental Imagery and Human Memory*, The Macmillan Press Ltd., London, pp. 43-59, 1980

Richardson, J.T.E., 'Imagery and the brain', in *Imagery and Cognition*, Cornoldi and McDanniel (eds.), Springer-Verlag, New York, 1990.

Richens, P., "The next ten years," in *Computers in Architecture Tools for Design*, F. Penz(ed.), Longman, Essex, 1992.

Richens, P., 'Does knowledge really help? CAD research at the Martin Centre', *Automation in Construction*, No. 3, 1994.

Riesbeck C. and R.C. Schank, *Inside Case-Based Reasoning,* Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1989.

Rittel, H.W.J. and M.M. Webber, 'Dilemmas in a general theory of planning', *Policy Sciences,* Vol. 4, 1973.

Rittel, H.W.J., 'Impressions of architecture 130: Notes and observations on Professor Horst W. J. Rittel's classic Design Methods course at Berkeley astaught circa 1969-1970', in *Design Method: theory, research, education and practice,* Vol.29 No.1, 1995.

Rosenman M.A. and J.S. Gero, "Creativity in Design Using a Design Prototype Approach," in *Modelling Creativity and Knowledge-Based Creative Design,* John S. Gero and M. Maher (eds.), Lawrence Erlbaum Associates, Inc., New Jersey, 1993.

Rowe, P., *Design Thinking,* MIT Press, Cambridge, MA, 1987.

Schmitt, G.N., 'Expert systems and interactive fractal generators in design and evaluation', in *CAAD futures '87,* Elsevier, pp. 91-106, 1987.

Schmitt, G.N. and W. Oechsline, 'Computer aided architectural design futures, in *CAAD futures '91,* G.N. Schmitt (ed.), Vieweg, Wiesbaden, 1992.

Schmitt, G, 'Design medium - design object', in *Proceedings of the 7th International Conference on Computer-Aided Architectural Design Futures*, R. Junge(ed.), pp.3-15, 1997.

Schön D.A., *The Reflective Practitioner*, Harper Collins, USA, 1983.

Schön, D., *The Design Studio: An Exploration of its Traditions and Potentials*, RIBA Publications Limited, London, 1985.

Schön, D., 'Designing: rules, types and worlds', *Design Studies*, Vol.9, No.3, 1988.

Schwartz, R., 'Imagery – there's more to it than meets the eye', in *Imagery,* N. Block (ed.), The MIT Press, Cambridge, 1981.

Shank, R.C. and R. Abelson, *Scripts, Goals, and Understanding: An Inquiry into Human Knowledge Structures,* Erlbaum, Hillsadale, NJ, 1977.

Shank, R.C., 'How much intelligence is there in artificial intelligence?, *Intelligence*, 4, pp.1-14, 1980.

Shepard, R. N., 'The mental image', in *American Psychologist*, No. 33, pp.125-127, 1978.

Shepard, R.N and J. Metzler, 'Upward direction, mental rotation, and discrimation of left and right turn in maps', in *Visual Cognition,* S.Pinker (ed.), The MIT Press, Cambridge, pp. 161-193, 1985.

Simon, H.A., *Models of Man: Social and Rational,* Wiley, New York, 1957.

Simon, H.A., 'The structure of ill-structured problems', *Artificial Intelligence,* 4, pp. 181-200, 1973.

Simon, H.A, *Administrative Behaviours* (3rd ed.), New York, The free press, 1976.

Simon, H.A., *The Science of the Artificial* (2nd ed.), MIT press, Cambridge, MA, 1981.

Sivaloganathan, S., N.F.O. Evbuomwan, A Jebb and H.P. Wynn, 'Design function development – a design system for the future', *Design Studies*, Vol.16, No.4, pp. 447-470, 1995.

Stefik, M, *Introduction to Knowledge Systems*, Morgan Kaufmann Publishers, Inc., San Francisco, 1993.

Sternberg, R. and P. Frensch, 'Intelligence and cognition, in *Cognitive Psychology*, M.W. Eysenck (ed.), John Wiley & Son, Chichester, pp.57- 96, 1990.

Swerdloff, L.M. and Y.E. Kalay, 'A partnership approach to computer-aided design', in *Computability of Design*, Y.E. Kalay (ed.), John Wiley & Sons, New York, 1987.

Thompson, D., *The Concise Oxford Dictionary*, (9th ed.), Clarendon Press, Oxford, 1995.

Trovey, M., 'Thinking styles and modelling system', *Design Studies*, Vol.7, No.1, pp. 20-30, 1986.

Tulving, E, 'Episodic and semantic memory', in *Organisation of memory*, E.Tulving and W.Donaldson (eds.), Academic Press, New York, 1972.

Ueda, K., 'The Fifth Generation Project', *Communication of the ACM*, Vol. 36, No. 3, pp. 48-76, 1993.

Ullman, D.G., 'The status of design theory research in the Unite States', *Design Studies*, Vol. 12 No. 4, 1991.

Ullman, S., 'Visual routine', *Cognition*, 18, pp.97-159, 1984.

van Sommers, Peter, *Drawings and Cognition: Descriptive and Experimental Studies of Graphic Production Processes*, Cambridge University Press, Cambridge, 1984.

Visser, W., 'Two functions of analogical reasoning in design: a cognitive psychology approach', *Design Studies*, Vol. 17, No.4, pp. 417-434, 1996.

Wade, J. W., *Architecture, Problems, and Purposes: Architectural Design as a Basic Problem-Solving Process*, John Wiley & Sons, New York, 1977.

Walsh, V. and O'Mara, 'A selection on Attention', in *The Cognitive Neuropsychology of Attention*, Lawrence Erlbraum, Sussex, 1994.

Weber, R., *On the Aesthetic of Architecture: A Psychological Approach to the Structure and the Order of Perceived Architectural Space*, Avebury, Aldershot, 1995.

Willem, R.A., 'On knowing design', *Design Studies*, Vol. 9, No.4, 1988.

Willem, R.A., 'Design and science', *Design Studies*, Vol.11, No.1, 1990.

Winnicott, D.W., *Playing and Reality*, Tavistock Publications; reprinted Penguin, 1971.

Winograd, T and F. Flores, *Understanding Computers and Cognition: A New Foundation for Design*, Addison-Wesley Publishing Company, Inc., Reading, 1987.

Young, R., *Mental Space*, Process press Ltd., London, 1994.

Appendix B: Published Paper

Andre Brown and Hwa Ryong Lee, 'A Mental Space Model',
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A MENTAL SPACE MODEL

Abstract

The architectural design process is often characterised a series of evolving ideas, and involving a cyclical process between design and visualisation (Simon, 1981). However, the nature of the internal representation still remains unclear. What is actually represented in a designers mental space and what drives and influences the mental design process? If we wish to programme a computer to mimic or work in tandem with the mental processes involved we need to make that representation and the associated cognitive processes explicit .

The ways that designers form mental representations are so diverse, personal, and often transient that it is not easy to externalise and articulate them in explicit terms. In order to propose a mental model, we can take in a particular psychological research approach; that of *introspective observation* from design drawing[1]. In doing so, we posit an assumption that the designer's drawing can be seen as an extension of the internal mental feature, and hence internal representation could be inferred from the analysis of external representation - the drawing or sketch. This approach contrasts with the protocol analysis approach where mental operations are inferred from words, what could be termed thinking aloud.

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1 Representation in Mental Space

In cognitive psychology, the term representation is used to describe internal models of individuals' environments and their actions in these environments. These models, provide individuals with information on the world and serve as instruments for the regulation and planning of behaviour (Dennis, 1991). That is, representation links behaviour and the human mind governing that behaviour.

In computational terms the typical representational system is a knowledge-base system that can be easily stored in memory and manipulated by an inference mechanism to activating a reasoned behaviour toward goals. Thus, the fields of cognitive science and AI have focused on the representation of knowledge, such as the acquisition, storage and manipulation of knowledge.

During designing, designers represent mental outputs internally in their personal mental space and externally on paper (or the like). The mental process in design can be explained as the symbolic processing of information, and includes generating design ideas, designing mentally and visualising mental images. It is clearly a representational activity, in that it involves information-processing but is expressed by a symbolic structure. However, design representation can be distinguished from, and is different to memory representation. Most significantly, the mode of representation in mental space is unique to the propositional mode in which that memory is generally stored and retrieved. That is, the designer is thinking visually and is hence representing ideas in what is mainly a graphical mode[2]. This makes it difficult to articulate design representation verbally.

Moreover, not all of the mental outputs in mental space are derived from a pre-stored memory, and hence they are represented incidentally with incomplete forms and as a part of thought processes that extend over only finite (short) periods of time. For these reasons, representing in mental space has very different function and structure from representation in a memory system.

1.1 Mental Space and Memory Systems

There are two prevailing concepts in computing design processes - the concepts of a memory system and that of a problem space. Many computer systems have supposed that the human brain is an information-processing system like a computer; and a set of formalised memory or database systems can support every step of problem-solving activity. As a result, they have focused on the construction of storable representations in long-term memory and on the retrieval of information from it.

However, mental space is different from a problem space. While a problem space refers to a place where the solver searches for potential solutions by applying a finite sequence of operations, mental space means a place that a design occurs in the mind. In problem space, design is regarded as a search process, and involves decision-making or knowledge-based activities. In the computational terms, while the problem space must be able to access declarative knowledge about facts in order to make inferences, mental space provides the designer with a space for exploring in an extension of a capacity for knowing and imagery.

So, what are the differences between representation in a memory and representation in mental space? While the former involves in *storing* perceptual experience and is preparatory for recall or recognition, the latter involves in *interpreting* experience and is developed through mental images into a particular design.

Morris and Hampson (1983) have suggested that two types representation exist - a new construction (imagination image) or a remembered experience (memory image): while imagination images must draw on memory information, a remembered experience will represent a reconstruction rather than an accurate reproduction of the visual images. The initially represented design ideas (that represent 'the remembered experience') are invented and recreated in mental space by the effects of imagery, independently of long-term memory. Thus, a mental space system would focus on refining and recreating information rather than on organising information and retrieving from structured memory.

1.2 The role of the Designer's Value System

A characteristic of Mental Space is that the objects or events in it constantly change their forms or properties and are always interpreted and reformed according to the designer's intended meaning (Kosslyn,1994; Winnicot, 1971). The interpretation seems to function as a filter that translates information between the outer world and inner experiences or between a new situation and a memorised event.

This filtering function occurs through the designer's value system. It affects the ways that the designer thinks, deals with the world and represents ideas. Each designer has the different value system; it makes the product of design different (even given the same project or designer). Lawson (1980) stated that design inevitably involves subjective value judgement: the designer's value system is itself affected by the exploration of objectives and what the designer finds to be possible. Likewise, the values in design are highly context-dependent, subjective and changeable in the course of the compromises and trade-offs between the various possibilities and criteria.

The designer's input derives from accumulated knowledge, experience or the shared image (in case of a group of people). It facilitates both the symbolic expression as true or false (descriptive value), and that as good or bad (relative value[3]) in a certain course of action (de Bono, 1994). These values are involved indirectly in design representation but will be embodied in decision-making, judgement, and finally design production. Such value-laden characteristics in mental representation make it extremely difficult to computerise the designer's mental space.

It can be argued that representation in mental space, which is different from representation in memory system and is influenced by the designer's value system. This implies that a mental space design system is totally different from a memory-based design model or system.

2 The Components of Design Representation

Denis (1991) defines representation as a human activity that consists in generating symbols. A symbol is something that stands for something else and it is a tool for representing a more complex idea into simplified image or knowledge. Such symbols permit the communication of enormously complicated, often abstract ideas with just a few lines, shapes or simple notes. For example, the rectangle, often in the early design stage, represents a room, the arrows refer to the movement of people or goods and bubble diagrams can imply the relationship between two spaces.

It is supposed, therefore, that any design is represented and refined in mental space, using with the symbols of picture-like or propositional format. These symbols do not only represent places or things, but they can also be an information that transfers a particular message or meaning. Thus, they are raw materials for representing design ideas and for performing the mental actions on the designer's mental space.

We propose three kinds of the abstracted constituents that represent or operate on information in mental space; that is, objects, events, and relationships. In mental space, objects symbolise the physical elements of design with its properties; relationships link objects or object and its properties; and events represent a design experience within a specific context. In other words, while the things that can be seen by the mind's eye are denoted as objects, the things that are invisible but can be conceived are represented as relationships, and both exist in a temporal and spatial situation as an event. These constituents function as the significant resources not only to represent internal images and concepts, but also to visualise them. Finally, they can be analogised as computational elements: structured data; algorithms; graphic primitive elements; or operators.

2.1 Objects

Buildings are, physically, regarded as the combination of objects such as walls, doors or materials. The objects are represented in mental space with a concrete symbol; a shape or form, each of which depicts something in the designer's mind rather than what is actually seen. Each object has some extent and volume, and certain name and function, rather than being represented with geometric primitive symbols such as a line, a square or a circle. Thus, it is observed that the objects have their own specific attributes such as name, location, forms, and movement.

Mental space can be committed also to the spatial analogy of moving through time. As the architect is sketching a plan, he takes part in moving, watching the changing relationship of objects in three-dimensional space, and at the same time, places himself within the mental space looking into the future. The movement therefore involves the elapse of time. For example, the designer can walk though virtual space; touch the surface and material; feel the sense of place; and watch the movement of himself and objects in the virtual space. For this reason, the mental space employed in design is an active four-dimensional space rather than a three-dimensional one.

2.2 Relation Information

Relation is some kind of connection between two things, and is to combine the same attributes or functions to form category. The architect represents the semantic relation of objects, as well as the visual properties of objects. During designing, they represent relationships, such as spatial, hierarchic, functional, environmental, and so on. For example we might say: living room must be adjacent to kitchen (spatial relation); elements-living room-cluster-buildings (spatial hierarchic relation); it serves for family's entertainment (functional relation); and it must be open to a green space (environmental relation).

Such relationships have accumulated as structured knowledge, information, or design resource that are meaningful in designing, design education or discipline. Thus, if the designer has more experience, he/she may have a more improved body of knowledge that contains various relations between objects and thus he can readily draw up solutions by using them.

However, many of relations represented in the designer's mental space seem to be loosely associated with each other. That is why there is no absolutely right answer for design decision-making. Moreover, the designer makes something, without ever knowing what is right. Accordingly, it is the more appropriate argument in design domain that there are no right or wrong answer (relation) in design, but only better or worse one (Wade, 1977).

In addition, the relations of design domain are, as Alexander and Poyner (1984) stated, those of a question of value as opposed to a question of fact, which can be only be judged by subjectively chosen criteria or values; there is therefore no basis for universal agreement. Even though all design objects can be composed by any relation, many of them are so loosely connected and so entangled that it is difficult to specify some causal condition and effects. Inversely, such unrestricted relationship leaves latitude in which the designer can present creative ideas.

2.3 Event Information

An event is, generally speaking, an incident, an occurrence, or a particular happening in a situation. Designed objects are connected loosely to their functions, activities, utilities, or such like. The relationships between objects are varied in time and space; and design is experienced at some place and in some time, that is, with its specific context.

Much of the information that architects deal with during design process can be classed as event-like. They are best described as 'in the case' or 'may be', not as 'if then' or 'should be'. It may be thought of as analogous to the narrative in literature as opposed to the description. Furthermore, such event information clings to personal experience and a specific context, and hence it cannot be learned by instruction but is achieved by the exercise of trial and error.

Events are represented in mental space as a whole experience, as both the features of objects and their semantic relations. Those are available in the form of a repertoire of particular cases or precedent examples, in terms of which the designers are able to see the new situation. By perceiving a new situation as an element or elements of a repertoire and by doing in the new situation as they have done before, they can make use of their past experience without exactly matching the same event.

In addition, event information can lead the designer to a creative solution by mutation or analogical thinking. Mutation is the deliberate action of changing features or attitudes of an object or concept in an unconventional manner. The purpose of mutation is to find new properties, functions and meaning of an old concept by looking a new situation from different perspectives (Maher and Zhao, 1993). Analogical reasoning has been known as the most prevailing strategies for architects to reach at new experience. It is useful to solve an unfamiliar problem from past perceptional experiences, without adequate or directly applicable information. Likewise, event information makes the designer readily access to existing design and it enriches and extend more the designer's mental space with representational variants on themes sensed within the meaning of the building.

While relation information serves for reasoning or decision-making, event information serves for analogy, mutation or design reference. In design system, the former is encoded in a memory system in the propositional mode, and the latter is stored as an episodic memory[4], specific knowledge, or a precedent case that can be merged and adapted into new situation, without deep inspection of the memory system.

3 Knowledge and Mental Space

Before discussing the roles of knowledge in mental space, I intend to make clear the definition of knowledge. Here in the information-processing community, knowledge is manifold and differs with each purpose; that is, it is often exchanged synonymously and confusingly with such other words as data, facts, or information, but each of these words does not adequately stand in place of knowledge. Giarratano and Riley classified knowledge as a part of a hierarchy as noise; data; information; knowledge; metaknowledge:

Data are items of potential interest; processed data are information that is of interest; knowledge represents very specialised information; and metaknowledge is knowledge about knowledge and expertise.

While information may be relevant to communicating and storing representations of knowledge, knowledge is concerned with thinking and interpreting the world, itself requiring the use of data and information. Patterson (1989) also states that knowledge combines relationships, correlation, dependencies, and the notion of gestalt with data and information. However, the relationships among data, information and knowledge are, in fact, so intertwined that they cannot be easily classified. That is, they might often represent the same things; their meaning differs according to a particular context they are used in. In this thesis, knowledge is in general considered as a state of knowing and understanding a fact, and in computer terms, it refers to all the information chunks that we have represented in memory, including design facts, principles, or experiences.

.1 Cognitive process and knowledge

Generally speaking, problem-solving activities are supposed as a series of conscious)ehaviours involving intelligence. Human intelligence involves a variety of capabilities, ncluding reasoning, understanding, learning. These abilities are derived from knowledge stored in the solver's memory through inferring and generalising from acquaintance with facts. That is, humans can understand in a situation using knowledge that we have acquired in other specific situations.

It is not an easy task to understand the intertwined nature of human cognitive activities and to explain the role of knowledge in human thought and action. Greene(1987). argues that knowledge plays the central role in interpreting the environment and that it influences on all human thinking, learning, speech and action as follows:

"... (knowledge) affects the way people perceive situations in the first place, which in turn activities previously learned procedures for dealing with the new situation. To complete the circle, the consequences of actions will themselves be stored in the form of new knowledge for deciding about future actions. This allows for the possibility of learning from new experiences, nothing procedures which have proved to be effective for dealing with a variety of situations."

Accordingly, knowledge has been regarded as the focus for explaining human thinking and activities, which can be explained with such psychological terms as cognition (the acquisition of knowledge) and cognitive process (representations and exploitation of knowledge). This cognitive approach has been applied to many areas as an identifiable theoretical standpoint for explaining human behaviour.

Schemata in memory theory are defined as an active organisation of past reactions, or of past experiences, which must always be supposed to be operating in any well-adapted organic response (Bartlett, 1990). In AI, schemata has been employed as a unit of pre-packaged knowledge stored in memory, together with a number of related ideas such as 'frame' and 'script' or as modules in software. They contain information about the typical problem goals, constraints, and solution procedures for that kind of problem. Thus, a knowledge base, as a metaphor for human memory, describes an organ that contains amounts of prior knowledge, which serve reasoning and solving problems. That is, if the problem solver - whether human or computer - finds a connection with prior knowledge, certain features of the problem may activate a schema for reasoning or solving the problem.

3.2 Knowledge in the Designer's Mental Space

Design questions can be described as one of two types. While the first kinds of questions are characterised as abstract, perception-like and visual mode, the second are as mathematical, memory-oriented, verbal mode. Encoding of the resulting different modes of information will follow different representation modes and different actions. The tool for handling the first kind of question is named imagery and that for the latter is knowledge, both of which are the main constituents in an operating mental process.

Whatever the modes of representation are stored and encoded in memory system - pictorial or propositional, one can change functionally to the appropriate format of representation as the mental process requires. That is, the designer has already some faculties of how to select relevant information and actions to achieve perceived needs. Those faculties are acquired through practice and experience.

In computer terms, knowledge is usually distinguished between knowledge of fact and knowledge for action; Anderson (1983) classified these two types as procedural and declarative memory. While declarative knowledge refers to knowing that something is true or false or that a certain element within particular properties exists; procedural knowledge is referred to as knowing how to do something.

Procedural knowledge in a design domain is all knowledge of *how-to's* that describes and predicts actions or plans of action. That is, knowledge that can be externalised as if/then verbal statement belongs to this category, and thus such knowledge is automatically triggered whenever if condition matches then action. As designers become more skilled in their tasks, they rely more on procedural and less on declarative knowledge. From this, in computational AI, production (or reasoning) systems, or generic systems usually focus on procedural knowledge in hope that the design process will be automated someday (Achten, 1997).

Declarative knowledge contains facts and design principles; for example, 'any living room must have at least one wall open to the outsider'. Such a schema labelled 'living room' may provide a lot of information that might help the designer to design a 'living room'. The design is fulfilled by reference systems that contain amounts of declarative knowledge in various ways such as a database, a knowledge base or a case-base.

Carrara et. al. (1994) proposed that design knowledge comprises three distinct, yet related, modalities: descriptive knowledge (what is being designed and how it performs); normative knowledge (why is it being designed); and operational knowledge (how is it being designed). Though the distinctions among these categories of knowledge are tautologically obvious, it is not immediately clear why they are needed and how they might be organised in a design system. The main reason for this is that their relationships are so interdependent that they perform a function together, rarely separately.

For example, the schema labelled a 'living room' serves not only to inform the designer, but it also prompts the need for a revision if the designer recognises that 'the living room is enclosed by others rooms'. That is, as a new problem is input, it initiates the activation of facts in declarative memory, and at the same time executes an action in procedural memory. In this way, design knowledge serves for design actions as well as for reasoning and solving problems.

3.3 The Roles of Knowledge in Solving Design Problems

What roles does knowledge play in designing? There is a strong brief in cognitive science that knowledge gives substance to the problem and guides to solve it. In this context, designing can be seen as a task to find a physical form that will achieve the stated objectives. Alternatives and ideas that can potentially satisfy the objectives are

proposed in mental space and they may be continually revised, or even abandoned. That is, as a design proceeds, designer gains new insights; new aspects of a situation become apparent; and then new solutions or ideas are generated.
In this process, knowledge functions to extend the boundary of the designer's mental space where the designer explores and search for a solution. From this reasoning, Logan and Smithers (1993) say that the development of a design is constrained by the experience and knowledge the designer has at that time. This demonstrates that knowledge and experience are valuable in understanding problem and making design.

3.3.1 Design Knowledge as References

Information theories have defined information as data that has been processed into a form that is meaningful to the recipient and is of real or perceived value in current or prospective actions or decisions (Davis and Olsen, 1985). When dealing with a new problem or confronting a judgement in a design process, the designer requires information that can provide design references for solving blocked problems.

Design seems to be knowledge-rich activity, as Lawson (1994) asserts, in that design requires us to have considerable amounts of knowledge beyond that which is stated in the problem description.

Consequently, the quality of solution depends on the solver's abilities to store, retrieve, and manage the related information. Information is converted in the designer's mind into design knowledge, some of which can be the means of solving a problem or some may ultimately become solutions. Through these processes, design knowledge or information can be used as a reference tool to develop a design and as a resource to make better decisions.

These notions can be the starting points for design information systems or design reference systems that supplement the limitations of human abilities in storing, retrieving and managing information or knowledge. That is, declarative information can be formalised as pre-structured knowledge in a computer and then this knowledge can support every step of designing in significant ways through cognitive processes. The system includes database systems, decision support systems, and communication systems, can provide newly updated and correct information to an agent's knowledge base or database.

3.3.2 Knowledge for Solving Design Problems

Simon (1973) argued that any problem - whether ill-structured or well-structured - has a potentially relevant knowledge base: there may be nothing other than the size of the knowledge base to distinguish between the characteristics of problems. The design problem is a typical ill-structured problem and requires an exhaustive bank of pre-structured knowledge -whether in a designer's memory or in a computer's knowledge-base.

Design conjectures and ideas do not, on the whole, arise out of the external information such as client's demands, norms and technological means, but come from largely the pre-existing knowledge of the instrumental sets, solution types and informal codes. In this context, knowledge is the results of interpretation and it depends on the sum of previous experience and on situatedness (Wignograde and Flores, 1986). Pre-existing cognitive schemata guide the designer to structure the problem in terms in which it can be solved. Then they trigger design actions or inform decisions taken in pursuit of design goals.

Information movements in systems such as generating, learning, or transforming information are performed on the basis of fully articulated knowledge. It is one of the goals of design studies to explicate design norms, strategies, technique or creative methods that the designer uses into a form of knowledge. Such design methods could be employed directly in designing in order to generate candidates and design solutions, and to predict and evaluate their expected performance. In this context, design knowledge is a *transportable substance* (Stefik, 1994) that can be perfectly formulated, recorded, and made ready for use in terms of the scientific method, and that can guide future design action. Moreover, in terms of the computer, such problem-solving systems aims to automate the design process with the hope that design knowledge can be externalised and thereby improve the quality of design decision-making.

However, any design - especially architectural design - is entangled with large quantities of elements, rules and facts, and relationships to be taken account, and thus it may require a very large, perhaps infinite mass of knowledge sets to tackle real design. Moreover, most of the knowledge presented by the designer - during design or after design - is not explicit; only a relatively small part is amenable to verbal description.

From this observation, the reason that the designer's work is inexplicable is, as Daley (1982) asserts, that this is simply because these processes lie outside the bounds of verbal discourse: that is, they are literally indescribable in linguistic terms. A major obstacle is to formalise and acquire design knowledge, then, to translate it into a computer program in a design system. As a result, the assumption that a set of complete knowledge can solve design problems has not been accepted in the computed design field: and is, maybe, a Holy Grail.

4 The Roles of Imagery in Mental Space

Image generations in mental space begin by retrieving information about the appearance of objects or the properties of events from a memory system. This information is stored randomly in the general form of pictures, propositions or both. When encoded a new information, a retrieved or generated mental image is then constructed as a concrete shape within mental space, and it develops finally to a design through a mental visualising process and drawing action. Here, it is hypothesised that imagery functions as another mechanism of the designer's cognitive process which can be distinguished from knowledge.

The distinct feature of imagery is that it can be conducted independently of memory. Psychological experiments which show that the totally, congenitally blind subjects can also experience visual imagery suggests that imaginal representations can be activated in working memory in the absence of long-term visual memory (Ernest, 1987).

But imagery is different from mental image. While the image is a visual representation in memory or the short-term retention of visual information in mental space, (mental) imagery is instrumental in retrieving information about the physical properties of objects, or about physical relationships among objects, that was not explicitly encoded at any previous time (Pinker, 1983). Furthermore, it contributes to transfer information in mental space. In addition, imagination is one of important tools in imagery, which leads the designer to be creative. That is, mental imagery is not simply a phenomenal experience, but a medium in which information about the visual appearance of physical objects can be depicted and manipulated in a mental space. Therefore, representing visual images in memory systems and mental space is only a low-level function of imagery. But at higher levels imagery can serve for aiding conscious thinking and problem solving, even creative thinking.

4.1 Imagery in Design Problem-Solving

It had been argued in the anti-imagery thesis that imagery is an irrelevant by-play of more abstract cognitive processes and, thus, has a purely 'epiphenomenal' status in cognition (Pylyslyn, 1973). Yet, increasing amounts of experimental evidence strongly suggest that imagery is of functional importance in information-processing and there are many types of problems for which imagery can provide short cuts to the final solution, such as through a visual analogue without the need to carry out an extensive logical analysis (Beveridge and Pakins, 1987).

Besides of the spatial tasks, Kaufmann (1990) argued the role of imagery in the general reasoning processes - deduction and induction. Deductive operations are translated into image comparisons, and then certainty of judgement may be reached, meanwhile, inductive operations are the anticipations of image, where a future state of affairs may be imagined on the basis of a previous sequence of events.

More precisely, Denis (1991) argues that there are three functional properties of images relevant to problem solving: the structural similarity, the integrative potential, and the transformations. That is, the advantages of images in problem solving are they have a structural organisation similar to that of perception and they maintain a large number of informational units together as a unified whole in a flexible and swift manner. Likewise, much cognitive psychology research illustrates how images can be used to improve performance on many cognitive tasks, including processing spatial relations among different parts of a object, reasoning through image comparison and anticipation and problem-solving in some specific domains.

Imagery can be used in reasoning or problem-solving as well as in retrieving appropriate information. It is identified that mental synthesis and mental modelling are the useful functions for design problem solving. More significantly, the relevance of imagery is linked to solving ill-structured problems characterised by novelty, complexity, and ambiguity such as the design problem (Kaufman, 1990).

4.2 Creative Thinking and Imagery

Design and creativity go hand in hand; especially it is the case in the early stage of designing. From the romantic view, creativity is seen to be inherent in the mind itself, the artistic talent given at birth. Jones (1969), named the design activities performed from intuition as the 'black box' and defined creativity as the mysterious leap of insight. Similarly, Archer (1984) also indicated that the creative leap from pondering the question to finding a solution is *the real crux of the act of designing.*

However, there is suggested another way of thinking about creativity, that is, thinking of creativity as centrally manifested in problem-solving activities. These attempts have been pursued cognitive psychologists and AI researchers effected by modern information theories (Dagupta, 1994). They suggest that creativity may not be all that mysterious and that it may simply be good problem solving (Reed, 1996). From this, they establish the general hypotheses that creativity is manifestly a cognitive process, which is not significantly different in nature from everyday thinking and reasoning and is also involved in a mental processing of symbolic structure.

These observations, regardless of whether computers can really be creative, have led design and AI researches to focus on a computational model for the non-routine or creative design (Gero and Maher, 1993). Reed identifies shifts in research emphasis in relation to the problem-solving paradigm: The 1970s focused on work on how people use general heuristics to search problem spaces; the 1980s on how acquisition of domain-specific knowledge is required to become an expert; and the 1990s on study of creativity by contributing new insights about imagery.

In contrast with traditional problem-solving domains, imagery theories have provided a new resource to explain creativity. It is generally accepted that imagery might play an important role in creative thinking, invention or scientific discovery, and could be used to guide the creation in absence of explicit instructions for how to do. In short, as Anderson (1989) argues, people draw on imagery to create something; creativity is the execution or expression of imagery, the communication of inner imagery to others.
Imagery is used not for the questions of simply correct or wrong but that of novel and useful.

Shepard (1978) argued the following relevances for creative thinking among characteristics of imagery:

(1) imagery is less constrained by tradition than language;
(2) the richness of imagery makes it possible to note significant details and relationships that are not adequately contained in purely verbal representations;
(3) the spatial character of images makes them directly accessible to potent competencies for spatial intuition and manipulation; and
(4) vivid images may constitute more effective substitutes for corresponding external objects and events than it is possible to achieve with a purely verbal representation.

Such properties of imagery as richness, vividness, and fluidity, lead the designer to think in highly novel and unexpected ways, to see a hidden part and relation in events, and hence to reach a creative solution. Thus, creative thinking means creative exploration in mental space.
In such exploration, imagery can be used as an incentive that generates or develops the designer's intuition and imagination to achieve a creative solution. These observations suggest that the appropriate role of computer role in the design domain, is

for providing an environment to motivate and enhance the designer's potential for creativity rather than to solve creative problems.

4.3 Interaction between Intuition and Intellect.

We support a further suggestion, that imagery can trigger and activate the mental interaction between intuition and intellect to attempt to solve a problem. As discussed in the previous section, intuition plays a major role in any creative activity and thus it is often called 'intuitive creativity'. Intuition derives from the designer's insights, emotions, or experiences. There is little doubt that intuition and intellect play a mutually interdependent role in generating design ideas and developing them (Lawson, 1980). Arnheim (1986) identifies this co-operation as follows:

> "Intuition is privileged to perceive the overall structure of configurations. Intellectual analysis serves to abstract the character of entities and events from individual contexts and defines them 'as such'. Intuition and intellect do not operate separately but in almost every case require each other's co-operation."

If intellect and intuition represent ends of a continuum rather than distinct types, a question emerges: what fills the gap between them? We suggest that imagery may hold this connecting role. Even though the psychological evidence must be further tested, current work suggests that the designer seems to use imagery in order to integrate knowing something and an instant insight.

5 Concluding Discussion

We have tried to account for the functions of mental space as a medium to reach a design solution, by articulating its components and the associated roles of knowledge and imagery. In doing so, it has been identified that a design consists of diverse representations consisting of objects, relations and events; these components have their own properties and function in the design process; and via the designer's knowledge and imagery they are operated on as information in mental space.

Design knowledge can aid mental operations - generating design ideas, developing design and even activating design action. In the design process, certain design knowledge may help the architect to generate a solution directly, some knowledge may exist to transform data into useful information, and some may aid conjecture. The former can be thought of as knowledge as design reference and the latter as knowledge for solving design problems.

In addition to knowledge, imagery is also a basic form of cognition, and it plays a central role in many human activities, ranging from navigation to memory to creative problem-solving (Kosslyn, 1994). In such a problem-solving process, the use of imagery can be considered as one of strategies which optimise the conditions for a representation. Thus, imagery-based strategies enhance the designer's problem-solving and creative capacities. Even though there is incomplete evidence, it is suggested that imagery can function for filling the gap between intuition and intellect, which may be the most important quality to harmonise knowing and imagination.

Knowledge and imagery do not work alone. In a design activity they are interdependent and this observation forms a basis for Mental Space theory. While the studies of knowledge are relatively easy to articulate and are well-established, imagery theories are still relatively contentious.

Even so, we suggest that this theory can be applied as a theoretical foundation not only for computation of designing but also to general design studies; that is, it could provide a theoretical background for explaining the subjectivity and variability of design. It may also provide a route towards better computed design.

Notes

1. As an alternative to protocol analysis, Galle (1992) examined designer's thought process in the early creative phase of sketch design using the method of introspective observation.

2. Denis's experiment shows that the designer has the highest visual image latencies of 36 professions. See. Image and Cognition, Harvester, New York, p.105, 1991.

3. de Bono calls the value of design 'the relativity of value', and he asserts that design is the process of exploring values, reconciling values and creating new values; thus value is at the heart of the design process.

4. Tulving proposed a division of memory into semantic and episodic memory. Semantic memory is defined as general knowledge about concepts that has been abstracted from individual experience. In contrast, episodic memories refer to a definite time and place located in our own personal histories. See, Tulving, E., *Episodic and semantic memory*, in Organisation of Memory, E.Tulving and W.Donaldson (eds.), Academic Press, New York, p. 32, 1972.

References

1. Achten, H., Generic Representations, PhD Thesis, Bouwkunde, TU Eindhoven, 1997.
2. Alexander, C. and Poyner, B., The atoms of environmental structure in Developments in Design Methodology, N. Cross (ed.), Wiley, Chichester, pp.123-133, 1984.
3. Anderson, J.R., The Architecture of Cognition, Harvard University Press Cambridge, 1983.
4. Anderson, Richard L., Art in Small-Scale Societies, Prentice-Hall, Englewood Cliffs, pp.131-132, 1989.
5. Archer, L. B., Systematic method for designers in Development in design methodology, N. Cross (ed.), Wiley, New York, pp. 57-82,1984
6. Arnheim, R., New Essays on the Psychology of Art, University of California Press, Berkeley, p. 13,1986.
7. Bartlett, F.C., Remembering, London, Cambridge University Press, 1932, quoted by David F. Marks, On the relationship between imagery, body and mind, in Imagery, Routledge, London, p.8, 1990.
8. Beveridge, M. and Pakins, E., Visual representation in analogue problem solving, Memory and Cognition, No. 15, pp. 115-147, 1987.
9. Block, N., 'Introduction: What is the issue?', in Imagery, The MIT Press, Cambridge, p.1, 1981.
10. Carrara, G., Y. E. Kalay and G. Novembri, 'Knowledge-based computational support for architectural design, Automation in Construction, 3, p.165-166, 1994.
11. Dasgupta, S. Creativity in Invention and Design, Cambridge University Press, 1994.

12. Daley, J., Design creativity and the understanding of objects, Design Studies, Vol. 3 No. 3, pp. 133-137, 1982.
13. David, G. and M. Olson, Management Information System: Conceptual Foundations, Structure and Development, McGraw-Hill (2nd ed.), p. 200, 1985.
14. de Bono, E., Parallel Thinking, Penguin Books, London, pp. 187-194, 1994.
15. Denis, M., Image and Cognition, Harvester Wheatsheaf, New York, 1991.
16. Ernest, C.H., Imagery and memory in the blind: A review, in Imagery and related mnemonic processes: Theories, individual differences, and applications, M.A.McDaniel and M.Pressley (eds.), Springer-Verlag, New York, pp. 218-138, 1987.
17. Gero, J.S. and M.L.Maher (eds.), Creativity and Knowledge-Based Creative Design, Lawrence Brlbaum Associates, NJ, 1993.
18. Giarratano, J. and G. Riley, Expert System, PWS-KENT Publishing Company, Boston, p. 64-66, 1989.
19. Greene, J., Memory, thinking and Language: Topics in Cognitive Psychology, Methuen, London, p. 14, 1987.
20. Jones, J. Christopher, The state-of-the-art in design method in Design method in Architecture, G. Broadbent and A. Ward (eds.), Lund Humphries Publishers Limited, p. 194, 1969.
21. Kaufmann, G., Imagery effects on problem solving in Imagery: Current Developments, Routledge, London., p.173, 1990.
22. Kosslyn, S.M., Image and Brain: The Resolution of the Imagery Debate, The MIT Press, Cambridge, p.1, 1994.
23. Lawson, B., How Designers Think, Butterworth-Heinemann, pp. 89-91, 1988.
24. Lawson, B., Design in Mind, Butterworth-Heinemann, p. 6, 1994.
25. Logan, B. and Smithers, T., 'Creativity and design as exploration', in Modelling Creativity and Knowledge-Based Creative Design, J.S.Gero and M.L.Maher (eds.), Lawrence Brlbraum Associate, New Jersey, pp. 139-175, 1993.
26. Maher, M.L., and F. Zhao, 'Dynamic associations for creative Engineering design', in Modelling Creativity and Knowledge-Based Creative Design, J.S. Gero and M.L. Maher (eds.), Lawrence Erlbaum Associates, NJ, pp. 329-351, 1993.
27. Morris, Peter E. and P.J. Hampson, Imagery and Consciousness, Academic Press, London, p. 67, 1983
28. Patterson, D. W., Introduction to Artificial Intelligence and Expert Systems,
29. Prentice-Hall International, Inc., p. 11, 1989
30. Pinker, S., Visual cognition: Introduction, in Cognition, op.cit., pp. 1-63.
31. Morris, Peter E. and P.J.Hampson, Imagery and Consciousness, Academic Press, London, p.4, 1983.
32. Pylyshyn, Z.W., What the mind's eye tells the mind's brain: A critique of mental imagery, Psychological Bulletin, No. 80, pp 1-24, 1973.
33. Reed, S. T., Cognition: Theory and Applications (4th ed.), Brooks/Cole Publishing Company, Pacific Grove, p. 4, 1996.
34. Shepard, R.N and J. Metzler, Upward direction, mental rotation, and discrimation of left and right turn in maps, in Visual Cognition, S.Pinker (ed.), The MIT Press, Cambridge, pp. 161-193, 1985.
35. Shepard, R. N., The mental image, in American Psychologist, No. 33, pp.125-127, 1978.
36. Simon, H.A., The structure of ill-structured problems, in Artificial Intelligence, 4, pp. 181-200, 1973.
37. Stefik, M., Knowledge Systems, Morgan Kaufmann Publishers Inc., San Francisco, p.295, 1994.
38. Wade, J. W., Architecture, Problems, and Purposes, p21, 1977.
39. Wignograde,T and F.Flores, Understanding Computers and Cognition, Addison-Wesley Publishing Company, Reading, pp. 70-79, 1986
40. Willem, R. A., 'On knowing design', p. 224, 1990.
41. Winnicott, D.W., Playing and Reality, Tavistock publications, Reprinted by Penguin, p. 118, 1971.