Experimental Approaches for Understanding Conceptual Design Activities

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Abstract

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Designers play an important and critical role in developing innovative product design, which is the key for a company to survive in the highly competitive market with ever-increasing demands from customers. However, how designers think, reason, judge, and make decisions has not yet been studied well. This thesis aims to develop experimental approaches to qualitatively and quantitatively understand designers' cognitive activities in order to explore product innovation in the early design stages.

To study designers' cognitive activities, a new protocol analysis method is developed. In the protocol analysis experiment, designers' activities were recorded when solving a design problem. Designers were interviewed to recall their design process immediately after finishing the design. Then, the recorded verbal data were analyzed by transcribing, segmentation and encoding for further analysis. In general, protocol analysis is used to transform the unstructured data collected from designers into structured data. Existing protocol analysis methods used to study designers' cognitive activities heavily depend on specific design problems, specific domains and the persons who analyze the protocol data.

The new protocol analysis method presented in this thesis is based on the concept of the state of design and recursive object model. It can be easily applied to any design problem and any domain. Using this method, the changes of designers' cognitive activities during the design process can be quantified. Some guidelines and recommendations for assisting designers to deliver an innovative design are summarized at the end of the present thesis based on the experimental results. The protocol analysis results have also been used to evaluate Environment-Based Design (EBD) as a descriptive design model; hence, EBD can be used as the theoretical foundation to illustrate, describe, and explain how designers conduct a design task.

Another part of my thesis is to simulate the design process by developing a virtual experiment. In the virtual experiment, the selected design problem: finite element mesh design, can be automatically solved using a program developed in the computer environment of Visual C++. Net 2003. Then, different settings of the parameters, different strategies, different formulations of design requirements, and different sequences for solving the design problem are simulated to compare the differences of meshes. Three routes leading designers to innovative designs are proposed and examined through this virtual experiment. Based on the three routes, an ANN-based element extraction method for finite element mesh design is developed to illustrate the feasibility of the three routes for changing design solutions.

Therefore, the two experimental approaches proposed in this thesis can be used for understanding design activities in a more systematic manner.

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Chapter 1
Introduction

1.1 Background and Motivation

Design is a general intellectual activity that goes into every part of human life. It not only influences our everyday lives, but also the development of manufacturing companies. Innovative design solutions in planning, materials, and manufacturing are enriching our lives and leading designers into new realms of possibilities, through today's major design disciplines such as urban design, industrial design, graphic design, engineering design, interactive media design, and social design. A better understanding of product innovation would help companies to manage and to control their product development in a more effective manner, thereby enhancing the companies' competitiveness in the global market. A typical design process includes several major stages: the gathering and the management of product requirements, conceptual design, embodiment design, and detailed design. At the beginning of a product design process, based on a request made by customers, designers start to identify the customer's real intent in order to gather all explicit and implicit requirements that the product must satisfy. The gathered product requirements are then specified in order to support the subsequent design process. The conceptual design includes the definition of the design problem, the identification and specification of product requirements, and the generation and evaluation of design concepts. After that, the embodiment design as well as the detailed design transform the generated concepts into product descriptions that can guide the implementation of the design solution.

Over the last few decades, a great deal of effort has been made to support embodiment design and detailed design. Study has shown that 70% of the cost of a product is determined by the decisions made in the early design stages (Ullman 2002). However, early design stages have not been well investigated. In addition, any design changes leading to a creative design can be made more easily and less expensively in the early stages rather than in the later stages. Therefore, the present research focuses on the early design stages or conceptual design. The early design stages include gathering and management of product requirements, definition of a design problem, specification of product requirements, concept generation and concept evaluation.

In the conceptual design, designers play an important and critical role in guiding the design process to achieve design breakthroughs and innovations. The understanding of designers' cognitive activities during the design process would provide guidelines and recommendations to designers for delivering an innovative design solution. A lot of studies (Free and Stern 1982; Liu 2000; George and Zhou 2002; Stempfle and Badke-Schaub 2002; Lofthouse 2004) have shown that how humans understand and solve a problem can affect the solutions a lot. For the same design problem, different designers may get different design solutions. To understand what factors could affect designers' decisions would help us understand designers' thinking and reasoning in the design process and integrate those factors into the design methodologies in order to deliver a successful design solution. Therefore, the present thesis aims to develop systematic experimental approaches to qualitatively and quantitatively understanding designers' cognitive activities, such as their problem-solving behaviors and thinking processes, in the exploration of product innovation in the conceptual design. Using the approach, the changes in designers' cognitive activities during a design process can be understood and quantified. Some guidelines and recommendations that assist designers to deliver an innovative design can be summarized from and based on the results of the present research.

1.2 Objectives

Although product innovation has been investigated ever since people started designing, there is no systematic approach to guiding designers in producing an innovative product. The objective of the present research is to develop effective and feasible experimental approaches to studying designer's cognitive activities and to understanding design properties. The specific aims are as follows:

1) To develop an experimental method to record designers' design activities and analyze designers' thinking and problem-solving behavior;
2) To evaluate a new design methodology as a descriptive design model to study how designers design using experimental results;
3) To investigate and validate the factors that stimulate designers to generate creative design using a virtual experiment;
4) To develop a new algorithm for a typical design problem using the observations from the experimental approaches.

The assumptions for the aims of this present research are 1) a design theory can be verified through empirical studies; 2) designer's cognitive activities can be studied and quantified through empirical approaches; 3) design activities can be simulated through computer simulation model.

1.3 Challenges in Understanding Design Activities

Understanding design activities, especially designers' cognitive processes, is very important and essential for developing tools to assist designers in delivering innovative product designs and to support different design behavior. However, some challenges exist in current design studies.

1) Most existing design theories and methodologies are developed based on expert experience and step-by-step procedures accumulated from design practice. Design theories and methodologies must be implemented by designers in order to deliver design solutions. To follow a design methodology is a logical and rational process whereas designers' thinking and problem-solving behavior is an intuitive and imaginative process. The two processes are in contradiction with each other.

2) Designers play an active and important role in guiding the design process to achieve design breakthroughs and innovation. To understand the designers' role in design creativity, it is important to study how designers know, perceive, make decisions, and construct behavior in the design process and investigate what factors could affect a creative design. Design research in this aspect is limited and lacks an efficient method.

3) Empirical approaches are important methods for observing and analyzing designers' cognitive activities. Existing empirical studies including verbal protocol analysis, virtual experiment and case studies have shed some lights on designers' cognitive activities, but there are no systematic and effective empirical approaches to studying designers' cognitive processes and verify the mechanisms and observations behind the design activities.

This present thesis targets these challenges by developing effective empirical approaches. A good design methodology can inspire designers' creativity and help designers deliver innovative design solutions. Thus, a new design methodology, Environment-Based Design is adopted as the theoretical background of this present thesis. This design methodology can be used to theoretically explain some common design properties and guide the analysis of the experimental results. A verbal protocol analysis method is developed to examine design properties and evaluate the environment-based design as a descriptive design model. In addition, a virtual experiment is conducted to examine and identify the factors leading designers to generate new designs. From the experimental studies of protocol analysis and virtual experiment, some recommendations and guidelines for assisting designers in delivering innovative design solutions are summarized.

1.4 Major Contributions

This present thesis was focused on the development of effective empirical approaches to understand designer's cognitive activities and investigate factors leading to creative design. The major contributions of the thesis work can be summarized as follows.

First, a new verbal protocol analysis method is developed for understanding designers' cognitive activities. The experiment for conducting the protocol analysis is designed to completely and accurately record designers' activities during the design processes while minimizing the interference of the experimental setting to the designers. A coding scheme for analyzing the experimental data is developed. The experimental results have shown that creative designers may consider more environment components and identify deeper relationships between environment components to generate design concepts. The comparisons between different designers' design processes demonstrated the routes leading designers to generate different design concepts. The proposed protocol analysis method can be applied to analyze other protocol data and study the human cognitive activities in other domains.

Second, a new design methodology, environment-based design is evaluated as a descriptive design model using the protocol analysis results. The environment-based design (Zeng 2004a; Zeng 2004b) was proposed by Zeng in 2004. An example of the protocol data is used to illustrate the process flow of the environment-based design and explain the four theorems implied in the environment-based design. It can be shown from the results that EBD can be a descriptive model to explain and describe how designers design.

Third, a virtual experiment is designed to simulate the three routes that could affect designers to generate different design solutions. The three routes are: formulating the design problem differently, changing the sequence of environment decomposition, and extending synthesis knowledge. The virtual experiment is designed based on a virtual environment to simulate the design process of the finite element mesh design. The results have shown that the three routes are validated through the experiment and can be used as strategies by designers to create different design solutions.

Last, the application of the observations from the experimental results has been investigated to propose a new ANN-based element extraction method for solving a finite element mesh design problem. Environment-based design methodology is used to guide the process of developing the algorithm of the ANN-based method and the three routes validated using virtual experiment are taken as cognitive strategies to develop the concepts in the ANN-based method. The numerical results have shown the new ANN-based element extraction method is effective for solving the finite element mesh design problem.

1.5 Thesis Structure

The rest of the present thesis is organized as follows:

Chapter 2 gives the literature review of the related research work involved in the present thesis.

Chapter 3 introduces environment-based design as the theoretical background for the present thesis.

Chapter 4 elaborates the design of the product-environment-based protocol analysis including the requirements analysis, the selection of design problem, the subjects, and the procedure of the experiment set-up as well as data processing and results analysis.

Chapter 5 evaluates environment-based design as a descriptive design model using an example of the protocol data.

Chapter 6 investigates the virtual experiment based on a finite element mesh design problem to simulate design activities.

Chapter 7 explains the application of the observations from experimental studies to develop a new method for solving the finite element mesh design problem.

Chapter 8 summarizes and discusses the research results from the experimental studies.

Chapter 9 gives the conclusions of the present thesis and suggestions for future work.

The logical relations among these chapters are given in the Figure 1-1.

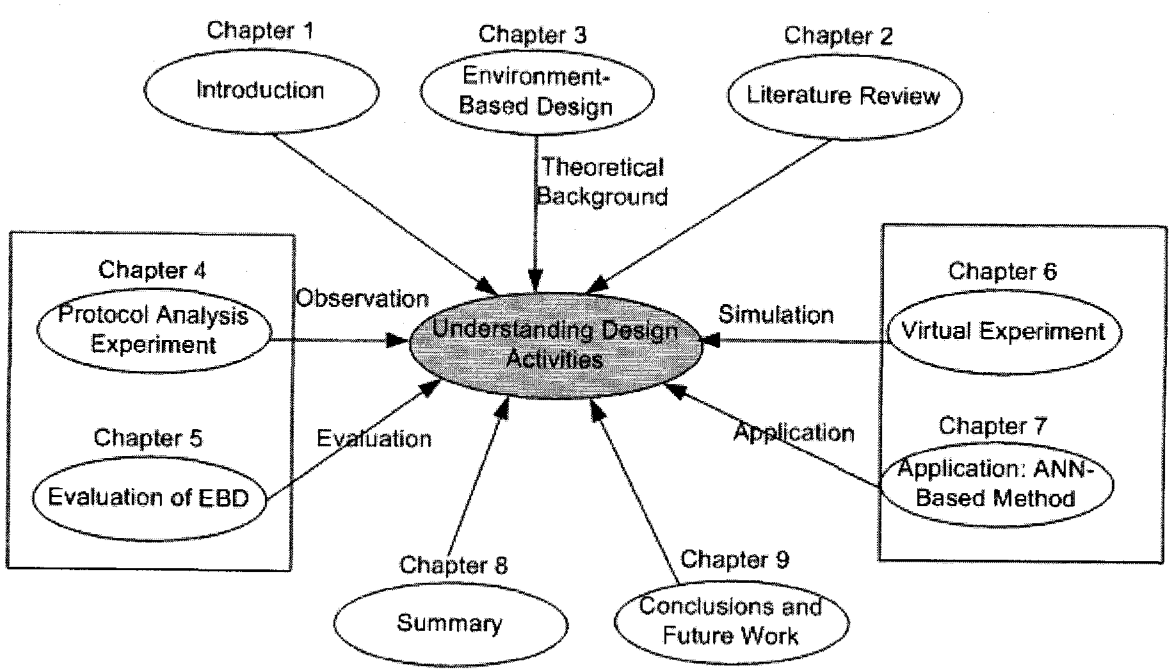


Figure 1-1 Structure of the thesis.

Chapter 2
Literature Review

2.1 Introduction

As the first step of exploring the research approaches to understanding design phenomena and to studying designers' cognitive activities, a few questions need to be addressed.

1) What are the characteristics of design activities and designers' general behavior during the design process?
2) What are the existing design theories, methodologies, and approaches in understanding design activities?
3) What is design creativity and what are the current studies in design creativity?

To answer these questions, it is essential to review the critical literature to discover the common properties of design activities, design theory and methodologies, and design creativity, thereby revealing the challenges in the research of understanding design activities.

2.2 Common Properties of Design Activities

Design activities are generally considered to be a form of complex problem solving (Simon 1969). Design problems are both ill-defined and open-ended. They are considered ill-defined because designers have, initially, only an incomplete and imprecise mental representation of the design goals (Eastman 1969; Simon 1973). Design problems are also considered to be open-ended as there is usually no single correct solution for a given problem, but instead a variety of potential solutions (Fustier 1989). Different designers can generate different design solutions for the same design problem. Generally speaking, any endeavor to understand design can be seen as an effort from two points of view, that of the product and of the process (Zeng 2004c). From the point of view of the product, the objects of the study of design include the designer, the product, the environment, and the mutual relationships of these three, as illustrated in Figure 2-1. The product can be a machine, a software package, a process, or an idea, etc. Anything except the product itself can be seen as its environment.

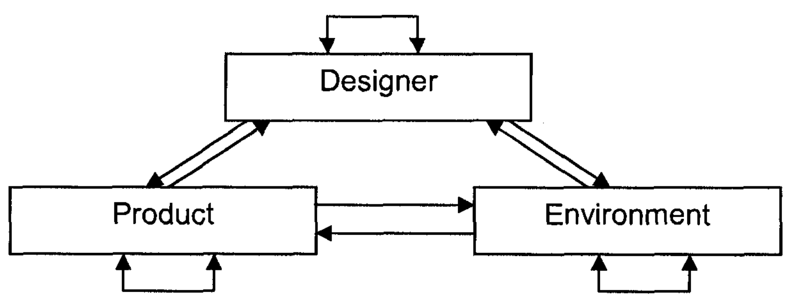


Figure 2-1 Objects of study of design: arrows represent relationships (Zeng 2004c).

From the point of view of the process, the objects of study of design include the problem formulation, the conceptual design, the embodiment design, and the detail design (Pahl and Beitz 1988), as shown in Figure 2-2. The four stages in the design process have been introduced in Chapter 1. The design process given in Figure 2-2 is an iterative process, in which designers may add, modify, or delete the existing components of the design stages. Each of these design stages involves designers, product, environment, and their mutual relationships.

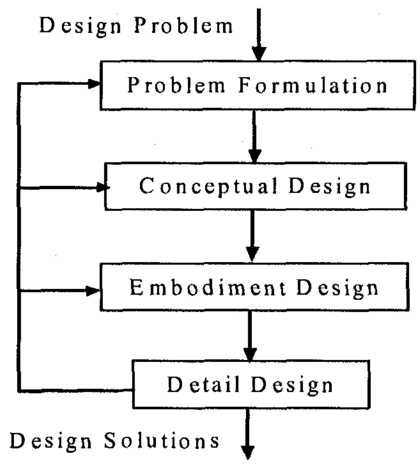


Figure 2-2 Basic design process.

Among these design stages, conceptual design plays the central role in ensuring design quality and product innovations. Any design changes leading to a creative design can be made more easily and less expensively in the conceptual design than any changes made in the embodiment design and the detail design. So this present research is focused on the conceptual design. The input for the conceptual design is some product requirements that define a design problem; the output is the descriptions of the product concepts. So the design process in conceptual design is a mapping between the product requirements and the product descriptions. In the design process, designers deliver a design solution by identifying and analyzing the product, the environment, and their mutual relationships. Next, the roles of designers, product and environment in the design process are discussed and some major design properties are summarized.

2.2.1 Designers

Design is an activity happening in the human rational system. Designers play a critical role in delivering a creative design. Designers first analyze, understand, and refine the product requirements from the design problem, and then decompose the design task into several sub-tasks. Then designers try to generate concepts to satisfy each sub-requirement based on their design knowledge and experience. Designers need to evaluate the generated concepts, choose the best one, and update the product requirements. Then, designers repeatedly analyze the product requirements, decompose the design problem, generate the concepts, and evaluate the generated concepts until all the product requirements are satisfied. Different designers may get different design solutions based on their design knowledge and experience.

According to designers' knowledge and experience, designers can be distinguished as novice designers and expert designers. Although both novice and expert designers share common actions in the design process, they deal with design problems in quite different ways. The differences between novice and expert designers have been discussed in much of the literature (Ho 2001; Seitamaa-Hakkarainen and Hakkarainen 2001; Kavakli and Gero 2002; Ahmed et al. 2003; Cross 2004; Atman et al. 2005). Cross (2004) has pointed out that the processes of structuring and formulating the problem are frequently identified as the key features of design expertise. Design knowledge and experience in a specific problem domain enable expert designers to quickly and easily formulate a design problem and to propose a solution. Another difference between novice and expert designers is that expert designers can generate a wider range of alternative solution concepts that may enhance the possibility of creative design.

Based on their design knowledge, designers can be categorized into designers with and without systematic design knowledge. Gunther and Ehrlenspiel (1999) have defined experienced designers from practice who have neither education at a university nor education in design methodology as p-designers and designers with education in design methodology at a university as m-designers. In the stage of clarifying the design task, p-designers do not clarify the task in detail at the start of the design process, but rather during the process, when the first conceptual ideas are elaborated. M-designers, however, begin the process by clarifying the task extensively before attempting the conceptual design. For both the p-designers and m-designers, the experienced designer is able to clarify a task in a short time. In the conceptual design stage, m-designers can document conceptual design more intensively and can elaborate more variants than can p-designers. P-designers prefer corrective variation and the variation of form. M-designers follow a phase-oriented procedure, while p-designers follow a sub-problem-oriented-procedure. It can be seen that the formulations of the design problem for m-designers and p-designers are different and hence the solutions are different.

There is no doubt that different designers show different abilities in solving different design problems. Even with the same design problem, designers may develop different design ideas and reach different solutions. This could be caused by the designer's emotion, experience, the stimulation from the environment, etc. Design is a nonlinear process, and a design problem may have multiple solutions. In different working conditions, designers may look at the design problem from different points of view and then decompose the design problem in different sequences, leading to different solutions.

2.2.2 Product and environment

As noted earlier, anything except the product itself can be seen as its environment. The product and the environment can have different components at each design stage. They evolve with the design process. In a design process, designers first identify the possible environment components around the product and then consider the interactions between the environment components and the product. Based on these interactions, the product requirements are generated. The product requirements may lead to some candidate solution concepts, which can be called the synthesis process. In the synthesis process a set of candidate solution concepts are proposed based on the product requirements. Then, the solution concepts are evaluated according to the designers' knowledge and experience, choosing the best solution concepts. This is an evaluation process. The evaluation process is used to screen candidate solution concepts against design requirements. The chosen design concepts become a part of product components. When generating new design concepts, the previously evaluated concepts will be taken as environment components to update the product requirements. The interaction of synthesis and evaluation gives rise to the final balanced design solutions.

It can be seen that during the design process, when generating new product components, designers identify different environment components and analyze different relationships between environment and product. So, environment is the driving force that pushes the evolution and development of a design process. During the design process, the environment consists of a series of components. If changing the sequence of environment decomposition, the environment components are different at each design stage and then the corresponding product components are different. So, it can be seen that changing the sequence of environment decomposition can change the design solution.

2.2.3 Design properties

Over the last five decades, the design research community has investigated various aspects of design, based on which some common properties of design problems and design processes have been recognized. Those properties can be used as empirical criteria to test an established design theory. If a theory leads to conclusions contradicting the properties, the theory should be rejected. Some of the major common design properties are shown below.

Property 1: Design is a recursive process in which a satisfying design solution must pass an evaluation defined by the design knowledge that is recursively dependent on the design solution to be evaluated (Zeng and Cheng 1991).

Property 2: Design is an evolving process that can be considered as a transition from abstract concepts to concrete descriptions (Suh 1990).

Property 3: A basic design process exists for all design problems. It includes two major processes: synthesis and evaluation. According to given design requirements, candidate design descriptions are generated in the synthesis stage. Then, the product descriptions and the corresponding product performance are evaluated against the design requirements to determine if the designed product satisfies the requirements in the evaluation stage. The process iteratively generates more and more concrete designs (Kryssanov et al. 2001).

Property 4: The design requirements may initially not be precise or complete; hence, the development and elaboration of design requirements becomes an integral part of the design process. An intermediate design result often intrigues new design requirements and refines the original design problem. This is called the ill-structured characteristics of design (Simon 1969; Simon 1973; Simon 1975).

Property 5: Design alternatives are not provided in advance in design problem solving. They must be found, developed, and synthesized by an exploration process, which is iterative and evolutionary in nature (Dorst and Cross 2001; Maher and Tang 2003). It cannot be expected that there is a deterministic solution for most design problems. There are no such things as well defined initial state, goal state, and state space for design problem solving.

Property 6: The designer is constantly faced with the problem of bounded rationality. In the model of bounded rationality it is self-evident that there are limitations on the cognitive and information processing capabilities of the designer's decision making. Traditional engineering design methods make much more use of satisfying criteria rather than of optimal specifications (Simon 1969; Simon 1982).

Property 7: Design is a creative act. One designer may even get different solutions when s/he does the same design, but at different times. Different designers may reach different solutions for the same design problem. Creative design is a random process (Crutchfield et al. 1986).

The following hypotheses are assumed as the routes leading to a new design based on the properties of the design process (Zeng 1992).

1) *Formulating the design problem differently changes design solutions.* It can be expected that formulating the design problem differently will get different requirements for a design problem. With different requirements, the solutions will be generated differently.

2) *Extending the synthesis knowledge leads to different design solutions.* For specified requirements, the more synthesis knowledge a designer has, the more concepts can be generated, which could lead to a better design solution.

3) *Changing the sequence of environment decomposition leads to different design solutions.* A design problem can be decomposed into various sub-problems. It can be expected that, following a different sequence of environment decomposition, the design solutions will be different.

These three routes provide alternatives to generate new design solutions and so increase the possibilities of generating creative design solutions. The research presented in this thesis explains and tests these hypotheses theoretically and experimentally.

2.3 Design Theory and Methodology

Over the last several decades, a variety of design theories and methodologies have been proposed, such as systematic design methodology (Hubka and Eder 1988; Pahl and Beitz 1988), Theory of Inventive Problem-Solving (TRIZ) (Altshuller 1984), decision-based design theory (Tribus 1969; Hazelrigg 1996; Allan and Mistree 1997), artificial intelligence-based design (Gero 2000), axiomatic design (Suh 1990), General Design Theory (Yoshikawa 1981), Formal Design Theory (Braha and Maimon 1998) and Axiomatic Theory of Design Modeling (Zeng 2002), etc. The systematic design methodology prescribes step-by-step procedures including four main stages: product planning and clarification of task; conceptual design; embodiment design; and detailed design (Hubka 1980; Hubka and Eder 1988; Pahl and Beitz 1988). Each of these stages can be decomposed into a sequence of operations with specific objectives. Another important achievement in systematic design is the Theory of Inventive Problem-Solving (TRIZ) which was developed by Altshuller and co-workers based on the analyses of a large number of patents to find general patterns (Altshuller 1984). Decision-based design (Tribus 1969; Hazelrigg 1996; Allan and Mistree 1997) is a methodology that uses the rules of decision theory and its related science in design to assist engineers in making better decisions in evaluating several alternatives and selecting the best one. Artificial intelligence based design research has three major issues: modeling multiple facets of mechanical products on different levels; representation of different types of design knowledge (Sainter et al. 1998); and mapping user requirements to some physical structures (Hsu and Woon 1998).The axiomatic approach in solving design problems was first proposed by Suh (Suh 1990). He identified two axioms, the independence axiom and the information axiom, in solving a design problem. There have some other work in developing and applying the axiomatic design theory (Rudolph 1996a; Rudolph 1996b; Marston et al. 1997; EI-Haik and Yang 1999; Jahangir and Frey 1999). The scientific exploration of mathematical design approaches include the General Design Theory (Yoshikawa 1981), the Extended General Design Theory (Tomiyama and Yoshikawa 1987), the Formal Design Theory (Braha and Maimon 1998) and the Axiomatic Theory of Design Modeling (Zeng 2002).

Endeavors have been made in understanding, simulating, and improving design from different points of view (Altshuller 1984; Eckersley 1988; Salustri and Venter 1992; Suwa and Tversky 1997; Akin and Akin 1998; Gorrti et al. 1998; Mc Neill et al. 1998; Gero 2000; Cross 2002; Turner and Turner 2003). These design research efforts can be grouped into three major categories: philosophical, deductive, and inductive. Next, the research work in the three categories is reviewed.

2.3.1 Philosophical studies

Philosophical studies investigate design problems, design objects and design processes through retrospection and speculation. The philosophical studies in design have enriched our understanding of design research and provided us with a macro-perspective to study design. Yoshikawa (1989) has indicated that design philosophy is the highest level of speculative thinking about the experience and manifestation of design, the role and position of design in society, the historical evolution of the design discipline, and the foundational basis of design thinking. Horváth (2004) stated, "Philosophy of design is often equal to a meta-theoretical framework for design theories by which epistemological and ontological clarity could be brought in (Love 2000), and often to a philosophy of practice (Evboumwan et al. 1996)." Design science (Alexander 1964; Simon 1969; Zeng and Cheng 1991; Orel and Trousse 1995), design thinking (March 1984; Zeng and Cheng 1991; Roozenburg 1992; Galle 1996), design history (Margolin 1992), design policy, design ethics (Herkert 1998), and design axiology (Findlay 1970) are considered as areas of current philosophy research.

With the philosophical understanding of design research, a design theory can be developed by using two systematic approaches: deductive and inductive studies, as is shown in Figure 2-3. Deductive studies attempt to establish design theories by using direct derivation from axioms whereas inductive studies aim to develop a design theory through the generalization from observations on design activities. These two approaches are taken as top-down and bottom-up strategies, respectively (Zeng 2002). A good design theory must follow and reflect the nature and characteristics of the design process. As stated by Zeng (2002), a design theory can be verified by applying it to case studies, by comparing it to the commonly accepted understanding of design properties through experiments, or by applying it to improve the design practices through managing the identified factors implied in the design process model established in design theories.

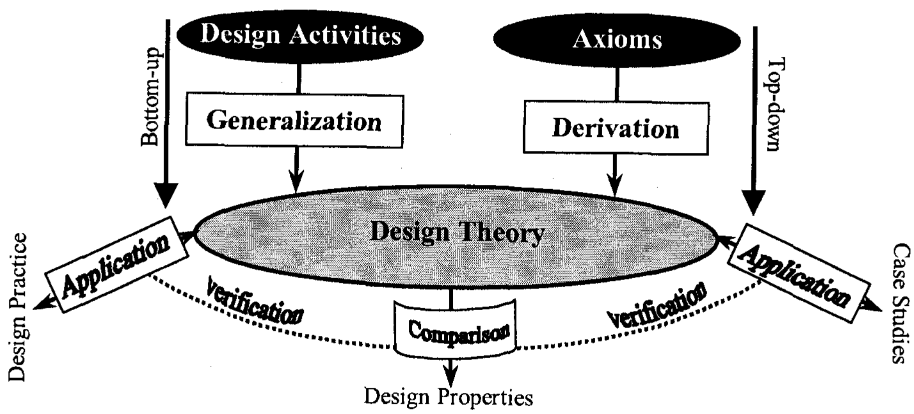


Figure 2-3 Two main strategies of design research (Zeng 2002).

2.3.2 Deductive studies

Deductive studies aim to establish the fundamental principles and theories for engineering design by identifying the common elements and disclosing the underlying order of design processes. The breakthroughs and innovation in understanding and modeling the design process depend on more scientific exploration of design, which can provide a formal representation of the design process. This kind of research targets the general design problem and the general model of design through the axiomatic approach. The representative work in the exploration of mathematical approaches is the General Design Theory (Yoshikawa 1981), the Extended General Design Theory (Tomiyama and Yoshikawa 1987), the Formal Design Theory (Braha and Maimon 1998) and the Axiomatic Theory of Design Modeling (Zeng 2002). Yoshikawa established the General Design Theory (GDT) in 1981. In his theory, Yoshikawa proposed three axioms: the axiom of recognition, the axiom of correspondence, and the axiom of operations. These axioms defined an idealized design performed by a superman who knows everything in the real world perfectly. Later, Tomiyama and Yoshikawa (Tomiyama and Yoshikawa 1987) extended the GDT by acknowledging that human recognition is imperfect. Reich produced a critical review of GDT (Reich 1995). He analyzed the assumptions made by GDT and the theorems it proved. It was found that GDT could not be an adequate description for real design. However, GDT is useful as a model of design, and it can offer some guidelines for building CAD systems; Tomiyama and his co-workers have applied it to CAD systems and to knowledge intensive engineering (Akman et al. 1990; Kurumatani et al. 1990; Tomiyama et al. 1990; Tomiyama et al. 1993; Tomiyama 1994). Braha and Maimon proposed a Formal Design Theory (FDT) in 1998 based on the science of the artificial proposed by Simon (1969) and on the pioneering work done by Yoshikawa and Tomiyama (Yoshikawa 1981; Tomiyama and Yoshikawa 1987). FDT analyzed ideal design and introduced the evolutionary process in the real design. There are five postulates in FDT. The first two deal with the representation of the product whereas the last three address the nature of the designer's knowledge. While FDT provides some guidelines to achieve the design solution, it requires a lot of heuristics and domain knowledge from designers. Based on the logic of design (Zeng and Cheng 1991) to classify the reasoning processes in human thought, Zeng and Gu developed a science-based design theory (Zeng and Gu 1999a; Zeng and Gu 1999b), which has been further developed into the axiomatic theory of design modeling (Zeng 2002).

2.3.3 Inductive studies

Inductive studies attempt to generalize design theories by observing and analyzing designers' design activities through experiences and experiments. Cross summarized the research methods for the study of engineering designers (Cross et al. 1992) and the research methods include interviews with designers, observations and case studies, protocol studies, controlled tests, simulation trials, and reflection and theorizing. Among them, verbal protocol analysis and case studies are commonly used in empirical approaches or inductive studies for generalizing design theories by observing designer's design activities. Protocol analysis has been used increasingly since the 1980's in investigating the process of designing and in understanding how designers design (Eckersley 1988; Stauffer and Ullman 1991; Lloyd et al. 1995; Purcell and Gero 1998; Atman et al. 2005; Jin and Chusilp 2006). Protocol analysis studies a subject's mental processes in accomplishing tasks by recording their spontaneous thinking aloud as running commentary, which will be subsequently segmented into the discrete atomic mental operations (http://www.informatics.susx.ac.uk/books/computers-and-thought/gloss/node1.html). Case study is a popular method used by researchers to produce new design theory, to verify a design theory or explain design phenomena. Yin (1984) defined the case study research method as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used. Inspired by the success of simulation and virtual experiment in many other fields such as construction (Li et al. 2003), hydrology (Weiler and McDonnell

2004; Weiler and McDonnell 2006), education (Marinov and Andonov 1997), computer science (Hirtz et al. 2002), and human experience (Takatalo et al. 2008), virtual experiment can be used to simulate design activities and human thinking as well as validate the general observations from the design activities. Next the existing studies in verbal protocol analysis, virtual experiment and case studies are reviewed.

2.3.3.1 Verbal protocol analysis

According to Newell and Simon (Newell and Simon 1972), "protocols are recording of subject's problem-solving behaviour which can be subsequently analyzed to identify the invariance in the subject's patterns of behaviour." Akin (1986) affirms that, "a protocol is the recorded behaviour of the problem solver which is usually represented in the form of sketches, notes, video or audio recordings." Protocol analysis is composed of five main steps: first, recording what subjects say during the experiment; secondly, transcribing the recorded data into texts; thirdly, segmenting the protocol data; fourthly, coding the segmented protocol data into different categories; and, finally, analyzing and getting observations from the encoded data. There are two major approaches of collecting protocol data: concurrent and retrospective verbal reports. In concurrent verbal report, subjects talk aloud while thinking aloud to solve design problems. In the retrospective verbal report, subjects are asked to recall their design process after completing design tasks. These two approaches are now generally accepted as important sources of data on subjects' cognitive processes in specific tasks.

Various protocol studies have been used in different disciplines to study human cognitive activities. The essential ones include mechanical engineering (Stauffer and Ullman 1991), software design (Guindon 1990), electrical design (Mc Neill et al. 1998), industrial design (Valkenburg and Dorst 1998), architecture design (Suwa and Tversky 1997), interior design (Eckersley 1988), etc. It is also a popular method for the study of human cognitive activities in psychology and cognitive science (Wagner and Scurrah 1971; Kintsch and Keenan 1973; Mandler and Johnson 1977; Card et al. 1980; Kant 1985; Kotovsky et al. 1985; Johnson and Thornton 1991; Toye and Leifer 1994; Kane et al. 1996; Sen 1997; Anderson and Potter 1998; O'Hara and Payne 1998; Benbunan-Fich 2001; Novick and Hurley 2001). This phenomenon indicates that protocol analysis has been accepted as a prevailing approach for elucidating the cognitive process of humans in different areas.

Protocol analysis is a prevalent method used to study designers' cognitive activities and problem-solving behavior during the design process. Currently, the important research groups in studying designers' cognitive processes using protocol analysis, include the engineering design centre at Cambridge University (Wallace and Burgess 1995; Keates et al. 2002; Ahmed et al. 2003; Crilly et al. 2004; Aurisicchio et al. 2006; Eckert et al. 2006; Maier et al. 2006), the centre for design research at Stanford University (Cutkosky and Tenenbaum 1990; Tang and Leifer 1991; Toye and Leifer 1994; Hong et al. 1996; Kane et al. 1996; Leifer et al. 1996; Son et al. 1996; Rajagopalan et al. 2001), the IMPACT lab at the University of Southern California in mental iteration using protocol analysis (Ishino and Jin 2006; Jin and Chusilp 2006), the design lab at Concordia University in developing new protocol analysis method and in studying designer's mental stress using protocol analysis (Yao and Zeng 2006; Zhu et al. 2007; Yao and Zeng

2007a), the key centre of design computing and cognition at the University of Sydney (Gero and Rosenman 1990; Gero and Mc Neill 1998; Mc Neill et al. 1998; Suwa et al. 1998; Simoff and Maher 2000; Suwa et al. 2000; Gero and Tang 2001; Kavakli and Gero 2001; Gabriel and Maher 2002; Kavakli and Gero 2002; Maher and Tang 2003; Gero and Kannengiesser 2004; Bilda et al. 2006; Bilda and Gero 2007), etc.

Protocol analysis methods have also been used by a lot of individual researchers to understand design activities. N. Cross at Open University has been engaged in design studies since the 1960s. He has analyzed the cognitive activities and abilities of designers through protocols and other studies (Cross 1990; Cross and Clayburn Cross 1995; Cross 1997; Cross 1999; Ho 2001; Seitamaa-Hakkarainen and Hakkarainen 2001; Kavakli and Gero 2002; Ahmed et al. 2003; Cross 2004; Atman et al. 2005; Kruger and Cross 2006). He has summarized his work in this area in his new book, "*Designerly Ways of Knowing*" (Cross 2006). K. Dorst (1995) at Technical University Eindhoven has summarized the new directions in protocol analysis and has conducted some research in protocol analysis (Dorst 1995; Dorst and Dijkhuis 1995; Valkenburg and Dorst 1998; Dorst and Cross 2001; Dorst and Vermaas 2005; Dorst and Royakkers 2006; Vermaas and Dorst 2007). O. Akin at Carnegie Mellon University has conducted some architectural research in protocol analysis (Akin 1986; Akin 1990; Akin and Lin 1995; Akin and Akin 1996; Akin and Akin 1998; Akin and Moustapha 2004; Ozkaya and Akin 2007). The Delft Protocol Workshop organized by Nigel Cross, Henri Christiaans and Kees Dorst in 1994 has brought together top international design researchers in the analysis of videos of designing using the method of protocol analysis. The book from the workshop, "*Analysing Design Activity*", has been much cited by the design research community (Cross et al. 1997). Ericsson and Simon in their book (Ericsson and Simon 1993) have reviewed major advances in verbal reports over the past decade, including new evidence on how giving verbal reports affects subjects' cognitive processes, and on the validity and completeness of such reports. They have also summarized the central issues covered in the book and have provided an updated version of their information-processing model, explaining verbalization and verbal reports. They have described new studies on the effects of verbalization, interpreting the results of these studies and showing how their theory can be extended to account for them. They also addressed the issue of completeness of verbally reported information, reviewing the new evidence in three particularly active task domains. They concluded by citing recent contributions to the techniques for encoding protocols, raising general issues, and proposing directions for future research. There are other research groups and individuals studying protocol analysis (Visser 1995; Visser 1996; Turner and Turner 2003; Cardella et al. 2006; Menezes and Lawson 2006; Visser 2006; Kim et al. 2007).

2.3.3.2 Virtual experiment

Design is a complex activity, involving artifacts, people, tools, processes, organizations, etc. Virtual experiments can provide a computer-simulated environment to simulate different real situations in order to understand the phenomena and the complexity of design. A computerized model is beneficial to simulate different design situations in a virtual environment and conduct virtual experiments to validate or explain some design phenomena. It is not only cost-effective, but also can be easily and quickly operated to present the real problem from many different perspectives in a virtual environment. Few publications in design research address virtual experiments to understand a design process. However, it has been widely used in various other research areas, such as construction (Li et al. 2003), hydrology (Weiler and McDonnell 2004; Weiler and McDonnell 2006), education (Marinov and Andonov 1997), computer science (Hirtz et al. 2002), and human experience (Takatalo et al. 2008). (Li et al. 2003) have proposed an integrated virtual reality system to generate virtual environment near to reality construction environment for the construction planner to perform construction activities in a real world manner in order to plan, evaluate, and validate the construction operations. (Weiler and McDonnell 2004; Weiler and McDonnell 2006) have proposed a virtual experiment approach to provide a well-founded basis for defining the first-order controls and linkages between hydrology and biogeochemistry at the hillslope scale and perhaps form a basis for predicting flushing and transport of labile nutrients from upland to riparian zones. Marinov and Andonov (1997) have shown a way of utilizing the virtual experiment technique in tribological education with reference to metal cutting. Hirtz el al. (2002) have provided a snapshot of immersive virtual reality (IVR) use for scientific visualization in the context of the evolution of computing in general and of user interfaces in particular. Takatalo et al. (2008) have presented a framework for measuring human experience in virtual environment. Ferrero and Piuri (1999) presented a simulation environment supporting experiments in a virtual laboratory by using WWW technologies, which allows a high number of people to access the system and benefit from advanced training without requiring creation of huge and expensive laboratories with many working benches.

2.3.3.3 Case studies

Case study is an important method used by researchers to produce new design theory, to verify a design theory or explain design phenomena (Odell 2001; Cottam et al. 2002; Luo et al. 2003; Yang et al. 2007). Yin (1984) defined the case study research method as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used. There are three types of case study method: exploratory, explanatory and descriptive. Exploratory case studies set to explore any phenomenon in the data which serves as a point of interest to the researcher. Explanatory case studies examine the data closely both at a surface and deep level in order to explain the phenomena in the data. Descriptive case studies set to describe the natural phenomena which occur within the data in question, for instance, what different strategies are used by a reader and how the reader use them. Case study method is well suited for inductively building a rich, deep understanding of new phenomena. However, case studies are complex because they generally involve multiple sources of data, may include multiple cases within a study, and produce large amounts of data for analysis (Soy 1997). A common criticism of case study method is its dependency on a single case exploration making it difficult to reach a generalizing conclusion (Tellis 1997). Yin (1984) discusses three types of arguments against case study research. First, case studies are often accused of lack of rigor; second, case studies provide very little basis for scientific generalization since they use a small number of subjects, some conducted with only one subject; third, case studies are often labeled as being too long, difficult to conduct and producing a massive amount of documentation (Chan 1990).

2.4 Design Creativity

Design creativity has been thought of as a mystery and has been attributed to the special talents of individual designers. Kryssanov et al. (2001) considered creativity as a cognitive process that generates solutions to a task, which are novel or unconventional and satisfy certain requirements. According to Encyclopedia Britannica, creativity is the ability to make or otherwise bring into existence something new, whether a new solution to a problem, a new method or device, or a new artistic object or form. The definitions of creativity tell us one key characteristic of creativity is something new. Hence, how designers think and reason about a problem to generate new designs may decide the creativity of the design solution. Therefore, it is essential to study designers' thinking and problem-solving behavior during the design process in order to understand the factors leading to design creativity.

Some researchers have studied what processes, strategies and problem-solving methods designers use to create designs based on empirical approaches. Roseman and Gero (1993) suggested four procedures by which creative design might occur: combination, mutation, analogy and first principles. One other creative design procedure with similar potential has since been added to this list: emergence (Gero 1994). Using the design of microprogramming as an example, Dasgupta (1994) points out that inventing is a goal-directed yet opportunistic act; thus, the design agent's freedom and capacity to use his knowledge contribute significantly to the design creativity. Akin and Akin (1996) studied creative problem-solving behavior and concluded: "Realising a creative solution, by breaking out of a FR, depends on simultaneously specifying a new set of FRs that restructure the problem in such a way that the creative process is enhanced. The new FRs must, at a minimum, specify an appropriate representational medium (permitting the explorations needed to go beyond those of the earlier FRs), a design goal (one that goes beyond those achievable within the earlier FRs), and a set of procedures consistent with the representation domain and the goals." After comparing three cases of creative design in three different domains, Cross (1997) concluded that there is a common "systems approach" to the design problem, but designers may frame their problems in a distinctive and sometimes rather personal manner, and "first principles" are the foundation of design problem solving. From the cognitive point of view, Wharton (1999) characterized creativity as a focused mental process in which "we are not making something from nothing. Rather, we are taking various existent elements and modifying them such that they interact in a new way". Bonnardel (2000) has conducted two experimental studies in a creative professional area: non-routine design and suggested ways to facilitate creative acts from designers. Dorst and Cross (2001) analyzed the protocol studies of nine experienced industrial designers and stated that "Our observations confirm that creative design involves a period of exploration in which problem and solution spaces are evolving and are unstable until (temporarily) fixed by an emergent bridge which identifies a problem-solution pairing".

In addition to the empirical studies on design creativity, there are a few studies to explore the mechanism of design creativity theoretically. Theoretical approach attempts to establish a formal model to capture the mechanism of creative design so that the results can be easily adapted to support the development of design tools. Based on the logic of design (Zeng and Cheng 1991), Zeng and Gu (1999a) speculated that a chaotic motion is implied in design creativity. Kryssanov et al. (2001) studied creative design using the notations of Algebraic Semiotics and clarified the nature of emergence in design: while emergent properties of a product may influence its creative value, emergence can simply be seen as a by-product of the creative process. Zeng et al. (2004) has argued that design creativity can be studied mathematically and proposed a formal mechanism of creative design based on design governing equation, which relates the design process to the chaotic motion.

2.5 Concluding Remarks

This chapter first examined the characteristics of design properties and the roles of designers, product and environment in the design process. And then some major design properties were summarized. Based on the design properties, three hypotheses of providing the alternatives leading to new design were proposed to be examined by this present research. The existing research in design theory and methodology was reviewed in three categories: philosophical, deductive and inductive. Finally, the definitions and the existing studies in design creativity were reviewed and discussed.

Chapter 3
Environment-Based Design

This chapter introduces a new design methodology: environment-based design (EBD) (Zeng 2004a; Zeng 2004b) as the theoretical background for the present thesis. EBD is derived from axiomatic theory of design modeling (Zeng 2002). Before introducing EBD, this chapter first briefly introduces axiomatic theory of design modeling in Section 3.1 for better understanding EBD. Section 3.2 introduces the process flow of EBD and the four theorems implied in EBD. One of the key methods for environment analysis in EBD is linguistic analysis. Recursive object model (ROM) (Zeng 2007) is a graphic language representing all the linguistic elements in technical English, derived from axiomatic theory of design modeling. Section 3.3 introduces ROM to illustrate the modeling of linguistic components graphically. Section 3.4 theoretically explains the hypotheses proposed in Section 2.2.3 using EBD.

3.1 Axiomatic Theory of Design Modeling

Axiomatic theory of design modeling is a logical tool for representing and reasoning about object structures (Zeng 2002). It provides a formal approach that allows for the development of design theories following logical steps based on mathematical concepts and axioms. The primitive concepts of universe, object, and relation are used in the axiomatic theory of design modeling. Their definitions can be found from the Random House Webster's Unabridged Dictionary as follows.

Definition 1: The universe is the whole body of things and phenomena observed or postulated.

Definition 2: An object is anything that can be observed or postulated in the universe.

It can be seen from the two definitions above that universe is the whole body of objects.

Definition 3: A relation is an aspect or quality that connects two or more objects as being or belonging or working together or as being of the same kind. Relation can also be a property that holds between an ordered pair of objects.

$$R = A \sim B, \exists A, B, R, \tag{3-1}$$

where A and B are objects. A~B is read as "A relates to B". R is a relation from object A to object B. Basic properties of relations include idempotent, commutative, transitive, associative and distributive.

Based on these concepts, the axioms of objects are defined in the axiomatic theory of design modeling.

Axiom 1: Everything in the universe is an object.

Axiom 2: There are relations between objects.

It can be seen from these two axioms that the characteristics of relations would play a critical role in the axiomatic theory of design modeling. It is essential to define a group of basic relations to capture the nature of object representation. Two corollaries of the axiomatic theory of design modeling are used to represent various relations in the universe.

Corollary 1: Every object in the universe includes other objects. Symbolically,

$$A \supseteq B, \forall A \, \exists B, \tag{3-2}$$

where B is called a sub-object of A. The symbol $\supseteq$ is inclusion relation. The inclusion relation is transitive and idempotent but not commutative.

Corollary 2: Every object in the universe interacts with other objects. Symbolically,

$$C = A \otimes B, \forall A, B \, \exists C, \tag{3-3}$$

where C is called the interaction of A on B. The symbol $\otimes$ represents interaction relation. Interaction relation is idempotent but not transitive or associative and not commutative either. The following rules hold for interaction relations:

$$\begin{aligned} A \otimes (B \cup C) &= (A \otimes B) \cup (A \otimes C) \\ (A \cup B) \otimes C &= (A \otimes C) \cup (B \otimes C) \\ A \otimes (B \cap C) &= (A \otimes B) \cap (A \otimes C) \\ (A \cap B) \otimes C &= (A \otimes C) \cap (B \otimes C) \end{aligned}$$

Based on the Corollary 1 and 2, the structure operation is developed.

Definition 4: Structure operation, denoted by $\oplus$, is defined by the union of an object and the interaction of the object with itself.

$$\oplus O = O \cup (O \otimes O), \tag{3-4}$$

where $\oplus O$ is the structure of object O.

The structure operation provides the aggregation mechanism for representing the object evolution in the design process.

Definition 5: The world is an object in the universe, which is made up of two objects: nature and the human thought. The world, nature, and the human thought are denoted by W, N and M, respectively, i.e.

$$W = N \cup M \tag{3-5}$$

By applying the rules holding for interaction relations and structure operation $\oplus$ defined in Equation (3-4) to the object W, the structure of the world, $\oplus W$, is

$$\begin{aligned}\oplus W &= \oplus(N \cup M) \\ &= (N \cup M) \cup ((N \cup M) \otimes (N \cup M)) \\ &= N \cup M \cup (N \otimes N) \cup (N \otimes M) \cup (M \otimes N) \cup (M \otimes M) \\ &= (N \cup (N \otimes N)) \cup (M \cup (M \otimes M)) \cup (N \otimes M) \cup (M \otimes N)\end{aligned}$$

Since $\oplus N = N \cup (N \otimes N)$, $\oplus M = M \cup (M \otimes M)$

the structure of the world, $\oplus W$ is represented as follows.

$$\oplus W = \oplus(N \cup M) = (\oplus N) \cup (\oplus M) \cup (N \otimes M) \cup (M \otimes N) \tag{3-6}$$

The four components of the structure of the world, $\oplus N$, $\oplus M$, $N \otimes M$ and $M \otimes N$ are defined as the natural system, the human rational system, recognition and action respectively.

In accordance to human commonsense, three axioms are developed to identify the nature of the reasoning and recognition processes in the human rational system.

Axiom 3: Human beings are bounded in rationality.

Axiom 4: Human beings do not recognize objects accurately.

Axiom 5: The causal relation is the only plausible relation in all relations between causes and effects.

Five theorems of design are logically derived based on the above five axioms. These theorems cover the construction of an engineering system, the formulation of design requirements, and the model of the design process. They are:

Theorem 1: An engineering system is made up of the product structure, the environment structure, and the mutual relations between the product and the environment.

Theorem 2: In an engineering domain, a limited amount of performance knowledge about a limited number of primitive products exists to represent the causal relations from actions to responses.

Theorem 3: Design requirements can be divided into structural requirements and performance requirements. Structural requirements are constraints on the product structure while performance requirements are constraints on the product performance. These requirements can be decomposed in terms of the product environment in which the product is expected to work.

Theorem 4: A product's performances can be analyzed through performance knowledge by gradually separating each component from the other components.

Theorem 5: Given a collection of design requirements, design solutions can be found by decomposing the product environment implied in the definition of design requirements. Each step of environment decomposition engenders a partial design solution, which redefines the environment and in turn the design requirements. This process halts when all design requirements are satisfied.

3.2 Environment-Based Design

Different from traditional design methodologies, Environment-Based Design Theory (EBD) (Zeng 2004a; Zeng 2004b) was logically derived from the axiomatic theory of design modeling (Zeng 2002), which was founded on the recursive logic of design (Zeng and Cheng 1991). EBD is a prescriptive model of design (which is a design methodology) that guides designers from the gathering of customer requirements throughout the generation and evaluation of design concepts. It is also a descriptive model of the natural design process that illustrates how designers conduct a design task (Yao and Zeng 2007a).

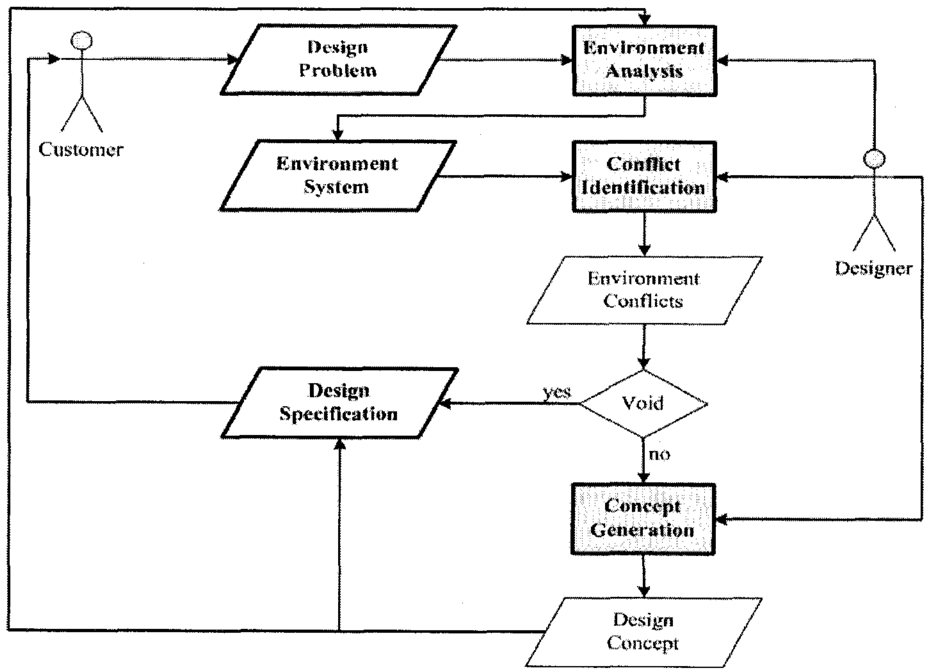


Figure 3-1 Environment-based design: process flow (Zeng 2004b).

As is illustrated in Figure 3-1, the environment-based design includes three main stages: environment analysis, conflict identification, and concept generation. These three stages work together to progressively and simultaneously generate and refine the design specifications and design solutions. The objective of environment analysis is to find out the key environment components, in which the product works, and the relationships between the environment components. From the environment implied in the design problem described by the customer(s), the designer will introduce extra environment components that are relevant to the design problem at hands. The results from this analysis constitute an environment system. One of the key methods for environment analysis is linguistic analysis (Chen and Zeng 2006; Wang and Zeng 2007). Following the environment analysis, conflicts should be identified among the relations between environment components (Zeng 2004b). At the third stage of EBD, a set of key environment conflicts will be chosen to be resolved by generating some design concepts. This process continues until no more unacceptable environment conflicts exist.

Based on the structure operation given in (3-4), a product system can be defined as the structure of an object (Ω) including both a product (S) and its environment (E).

$$\Omega = E \cup S, \forall E, S[E \cap S = \Phi], \tag{3-7}$$

where Φ is the object that is included in any object.

The product system ($\oplus\Omega$) can be expanded as follows:

$$\oplus \Omega = \oplus(E \cup S) = (\oplus E) \cup (\oplus S) \cup (E \otimes S) \cup (S \otimes E), \tag{3-8}$$

where $\oplus E$ and $\oplus S$ are structures of the environment and the product, respectively; $E \otimes S$ and $S \otimes E$ are the interactions between the environment and the product (Zeng 2002). A product system can be illustrated in Figure 3-2.

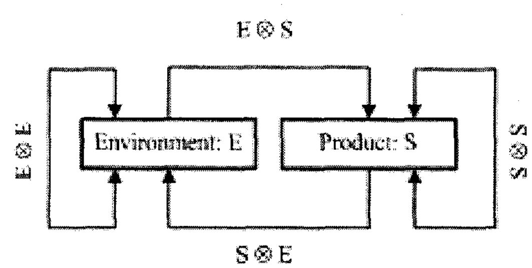


Figure 3-2 Product system (Zeng 2002).

In the design process, any previously generated design concept can be indeed seen as an environment component for the succeeding design. As a result, a new state of design can be defined as the structure of the old environment (Ei) and the newly generated design concept (Si), which is a partial design solution.

$$\oplus E_{i+1} = \oplus(E_i \cup S_i). \tag{3-9}$$

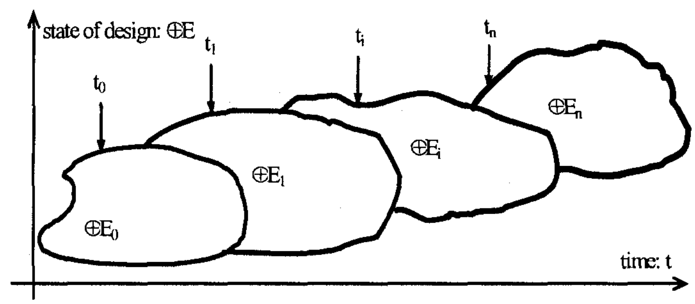


Figure 3-3 Environment based design: mathematical model (Zeng 2004a).

The evolution from the design state $\oplus E_i$ to the design state $\oplus E_{i+1}$ is governed by the following design governing equation (Zeng 2004a),

$$\oplus E_{i+1} = K_i^s(K_i^e(\oplus E_i)), \tag{3-10}$$

where K_i^s and K_i^e are synthesis and evaluation operators (Zeng and Gu 1999a; Zeng and Gu 1999b), respectively.

The two operators, K_i^s and K_i^e, correspond to two major phases in the design process: synthesis and evaluation. The synthesis process is responsible for proposing a set of candidate design solutions based on the design problem. It stretches the state space of design. The evaluation process is used to screen candidate solutions against the requirements in the design problem. It folds the state space of design. The interaction of both synthesis and evaluation processes gives rise to the final balanced design solutions, which can be illustrated in Figure 3-4.

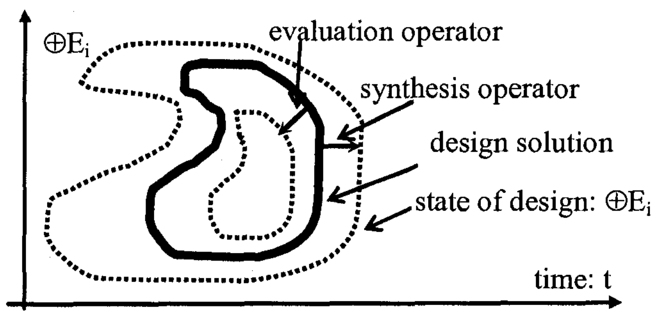


Figure 3-4 State space of design under synthesis and evaluation operators (Zeng and Gu 1999a)

The EBD process solves the design governing equation by following the procedures below (Zeng 2004b):

Step 1: Environment analysis: define the current environment system $\oplus E_i$.

$$\oplus E_i = \oplus(\bigcup_{j=1}^{n_e} E_{ij}) = \bigcup_{j=1}^{n_e}(\oplus E_{ij}) \cup \bigcup_{j_1=1}^{n_e}\bigcup_{\substack{j_2=1 \\ j_2 \neq j_1}}^{n_e}(E_{ij_1} \otimes E_{ij_2}). \qquad (3\text{-}11)$$

Step 2: Conflicts identification: identify conflicts C_i between environment components.

$$C_i \subset \bigcup_{j_1=1}^{n_e} \bigcup_{\substack{j_2=1 \\ j_2 \neq j_1}}^{n_e} (E_{ij_1} \otimes E_{ij_2}). \tag{3-12}$$

Step 3: Concept generation: generate a design concept s_i by resolving a group of chosen conflicts. The generated concept becomes a part of new product environment for the succeeding design. The design process continues with new environment analysis until no more undesired conflicts exist, i.e., $C_i = \Phi$.

$$\exists c_{ik} \subset C_i, c_{ik} \rightarrow s_i, \oplus E_{i+1} = \oplus(E_i \cup s_i). \tag{3-13}$$

There are four theorems implied in EBD: 1) Theorem of recursive logic of design; 2) Theorem of source of product requirements; 3) Theorem of dynamic structure of design problem; 4) Theorem of design driving force.

(1) Theorem of recursive logic of design. A design solution must pass an evaluation defined by the design knowledge that is recursively dependent on the design solution that is to be evaluated (Zeng and Cheng 1991).

Based on this theorem, a design process is composed of a series of design states defined by both product descriptions and product requirements, as is shown in Figure 3-5 (Zeng 2004a).

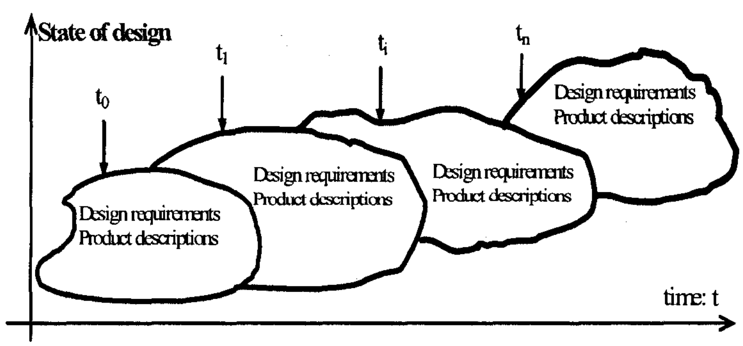


Figure 3-5 Evolution of the design process.

(2) Theorem of source of product requirements. All the product requirements in a design problem are imposed by the product environment in which the product is expected to work (Zeng 2004a; Chen and Zeng 2006).

This theorem implies that the driving force of a design process comes from environment, which includes natural human, and built environments (Zeng 2004a); therefore, product requirements can be defined by environment components in which the product is expected to work. Based on this theorem, product requirements are included in the environment structure $\oplus E$, which is the state of design and is defined as in equation (3-9).

The most important implication of this theorem is that the purpose of design is to change environment if the combination of conflicts among the components in the current environment produces enough driving forces, which can be derived from $\oplus E$, to start a design process.

(3) Theorem of dynamic structure of design problem. In the design process, design solutions to a design problem may change the original design problem, if the design solutions are different from their precedents, either by refinement or by alteration (Zeng et al. 2004).

(4) Theorem of design driving force. The driving force behind the design process is the undesired combined conflicts existing in an environment system. A design process continues until no such conflicts exist. This theorem is illustrated in Figure 3-3.

3.3 Recursive Object Model

Recursive object model (ROM) developed by Zeng (Zeng 2007) is a graphic language representing all the linguistic elements in technical English, derived from axiomatic theory of design modeling. Design problems are represented by language descriptions and design processes are described by designers in natural language. Language is a symbol system human beings used to describe the universe (Turner 1971). The symbols in a language may also fulfill certain structural functions in the language pattern so that ideas and objects can be combined to form more complex meanings (Turner 1971). ROM can be used to collect, organize, interpret, and analyze the characteristics by inferring from multiple object relationships implied in the natural language. As can be seen from Table 3-1, two objects and three relations are included in the ROM diagrams.

Table 3-1 Symbols in ROM

Type	Symbol	Graphic Representation	Description
Object	Object	$\boxed{O}$	Everything in the universe is an object.
	Compound Object	$\boxed{\boxed{O}}$	It is an object that includes at least two objects in it.
Relations	Constraint Relation	$\bullet\!\!-\!\boxed{\xi}\!\rightarrow$	It is a descriptive, limiting, or particularizing relation of one object to another.
	Connection Relation	$\text{- - -}\boxed{\iota}\text{- -}\!>$	It is to connect two objects that do not constrain each other.
	Predicate Relation	$-\!\boxed{\rho}\!\rightarrow$	It describes an act of an object on another or that describes the states of an object.

3.4 Theoretical Interpretation of Design Activities

Instead of interpreting all design activities, the equations (3-11) to (3-13) are used to interpret the three routes leading to new designs, given in Section 2.2.3. The details are given in (Zeng 2004b).

(1) Formulating the design problem differently changes design solutions.

The formulation of a design problem is included in the environment system $\oplus E_i$ (Zeng 2004a). The inclusion or exclusion of an environment component E_{ij} will lead to a change of $\oplus E_i$. In addition, in formulating a design problem, designers may choose to group different environment components as one assembly. This will also lead to a change of $\oplus E_i$. This can be seen from different activities between novice designers and expert designers. Since these two types of designers have quite different experience, they usually apply different methods to formulate the problem. As a result, they get different solutions. Even for the same designer, if he or she changes a perspective, the problem will be formulated in a different way and then the solution will be different. Consequently, the object C_i may be changed. This changes the initial condition of the design process, which could result in the change of design solutions.

(2) Extending synthesis knowledge leads to different design solutions.

The extension of synthesis knowledge will change the relation $\exists \mathbf{c}_{ik} \subset \mathbf{C}_i, \mathbf{c}_{ik} \to \mathbf{s}_i$. There are a few possibilities: first, more conflicts can be chosen at the same time to generate a design concept s_i; and secondly, the same design conflict c_{ik} may be resolved by different design concept s_i. Both cases will update the environment system $\oplus E_{i+1}$ differently.

When design conflicts are identified by analyzing the relations between environment and product, designers will use their knowledge and experience to generate some candidate solution concepts. The number and quality of the design concepts largely depend on designers' knowledge and experience. That is also a big difference between novice and expert designers. The generated concepts need to be evaluated to satisfy the specified product requirements. Novice designers often lack the ability of evaluating the generated concepts correctly, and hence finally fail to generate a good design solution. When designs by a novice designer and an expert designer are compared, a big difference can be found in the design solutions. The newly generated concepts are considered as the environment components and analyzed by combing other identified environment components for generating other design concepts. This process is represented as $\oplus E_{i+1} = K_i^s(K_i^e(\oplus E_i))$, where K_i^e and K_i^s are evaluation and synthesis operators, respectively. It can be seen that some new and different primitive products may be generated for a specified environment part by extending knowledge. Therefore, extending knowledge can help designers generate more candidate solutions concepts, and so increasing the probability of generating a good concept. As a result, a new design problem is generated, which may lead to new design solutions.

(3) Changing the sequence of environment decomposition leads to different design solutions.

In environment-based design theory, after the design conflicts C_i are identified, there exist many ways to choose the conflict to be resolved, which is based on the decomposition of the environment. Generally, no two designers have exactly the same design knowledge, so they will use different ways to decompose the environment. Different sequences of environment decomposition may give rise to different reformulation of the design problem when designers apply their synthesis knowledge. As a result, the final solution may be different.

In summary, design is a dynamic and recursive process and many factors could lead to new design solutions. From the analysis of design properties, it can be observed that three routes could lead to a new design. Those have also been theoretically interpreted by the EBD theory.

3.5 Summary

This chapter has introduced the theoretical background for the research presented in this thesis. Axiomatic theory of design modeling provides the logical tool for studying design activities. Environment-based design is a new design methodology developed based on axiomatic theory of design modeling. EBD provides the theoretical foundation of explaining the observations and properties from design activities. Experimental studies will be introduced in Chapter 5 to examine design properties and evaluate the EBD methodology. Recursive object model and axiomatic theory of design modeling will be used to analyze the data collected in the experimental studies.

Chapter 4
Product-Environment-Based Protocol Analysis Experiment

4.1 Introduction

Protocol analysis is an important approach to studying designers' thinking processes and problem-solving behaviors in order to understand design activities. Cross (2001) stated that "Of all the empirical research methods for the analysis of design activity, protocol analysis is the one that has received the most use and attention in recent years. It has become regarded as the most likely." This present thesis proposes a product environment-based protocol analysis for understanding design activities. The proposed protocol analysis method is designed based on the requirements analysis of designing protocol experiments, which includes defining the experimental objective, experiment set-up, transcription, segmentation, encoding as well as data analysis. This experiment is designed to completely and accurately record designer's cognitive activities and behaviors while minimizing the interference to the designers during the design process. The segmentation is based on the concept of design states which reflect the characteristics of the design process. The critical part for analyzing the protocol data is the coding scheme, which is developed using the concept of design states and the recursive object model based on the axiomatic theory of design modeling. The further qualitative and quantitative analysis on designers' cognitive activities can be easily and accurately summarized from the encoded protocol data. This present research has also been compared with other existing protocol analysis methods. The protocol analysis method proposed in this research can be applied to analyze other protocol data and study the human cognitive activities in other domains.

This rest of the chapter is organized as follows. Section 4.2 gives the review of protocol studies in design and points out the challenges in developing effective protocol analysis methods. Section 4.3 conducts the requirement analysis of designing a protocol analysis experiment. Based on the requirement analysis, the experiment is designed, as introduced in Section 4.4. The method of data collection is explained in Section 4.5. The design solutions generated by the subjects are evaluated in Section 4.6. Section 4.7 investigates the data processing and analysis based on the collected protocol data. The results and discussions are conducted in Section 4.8. Section 4.9 compares the present protocol analysis method with other protocol studies. Finally, the proposed protocol analysis method is summarized in Section 4.10.

4.2 Review of Protocol Studies in Design

Section 2.3.3.1 has introduced the definitions of the protocol analysis method, reviewed the protocol analysis studies in different disciplines, and summarized the research groups and individual researchers in using protocol studies to understand design activities. This present section elaborates the development of recent protocol studies in design. The two important approaches of data collection in protocol studies, concurrent report and retrospective report, are compared. The problems in existing protocol studies are summarized.

The first report of protocol studies on design activity was that of (Eastman 1970) who studied architects in the late 1960s. Eastman showed the diversity of constraints and the significance of representational language in intuitive design. The studies of protocol analysis in design have been growing increasingly since the 1980's in investigating the process of designing and in understanding how designers design. In 1988, Eckersley presented a model-based protocol analysis method, which is used to analyze, quantify, and statistically manipulate the designer's verbal behavior in order to reveal a unique and scientifically rigorous facsimile of problem-solving processes. In 1991, Stauffer and Ullman observed five mechanical engineers engaged in open-ended design problems and divided the designers' actions into 'operations' of short durations. In 1994, Lloyd and Scott presented a discipline-independent cognitive framework and applied it to a protocol analysis study of five engineering designers; their results indicated that the designer's experience plays a key role in determining the design process. Gero and Mc Neil (1998) developed and applied a methodology that uses protocol studies to investigate the process of designing, in which a coding scheme is proposed to articulate different aspects of the individual designer's behaviors and to distinguish the designing behaviors of different designers. Atman et al (1999) summarized several general characteristics of successful design processes by identifying the differences and similarities underlying freshmen and senior's design processes exemplified by their verbal protocols. Dorst and Cross (2001) validated the observations from the protocol data of nine experienced designers with the model of creative design proposed by Maher, et al. (1996). Akin and Moustapha (2004) studied six architects' protocol sessions to better understand the specific cognitive processes contributing to architecture massing. Jin and Chusilp (2006) used protocol analysis to validate the proposed cognitive activity model of conceptual design.

There are two major approaches in protocol analysis to collect protocol data: concurrent verbalization and retrospective verbal report. The method of concurrent verbalization requires the subjects to talk aloud about what they are thinking as they go about trying to solve various problems. By contrast, the method of retrospective verbal report leaves the designers alone without any interference before they have completed their design tasks. The designers are then asked to recall their design process and are reminded to answer some questions if they overlook any information. Some researchers have argued the respective effectiveness of these two approaches (Davies 1995; Lloyd et al. 1995; Santos-Eggimann et al. 1997; Kuusela and Paul 2000; Gero and Tang 2001). Lloyd et al. (1995) argued that although concurrent verbal reports can reveal some aspects of design thinking, there are many types of design thinking that remain impervious to concurrent verbalization requiring different methodologies for analysis. Suwa et al. (1998) employed retrospective report to reveal the perceptual interactions between a designer and his own sketches because they think that talking aloud concurrently may interfere with participant's perception during their sketching activities. Concurrent reports have their advantages in tracking designers' thinking behavior at any time in the design process, but some designers may not be capable of describing certain mental operations. Talking aloud may inadvertently affect the thinking process. In retrospective protocols, designers might recall their design process only partially and selectively. This effect can be reduced by showing the designers the video that recorded their design process and by asking them questions as memory cues.

The existing protocol studies have shed some lights on how protocol analysis method can be used to analyze designers' cognitive processes and problem-solving behaviors. They have extraordinarily advanced our understanding of design. However, the experimental set-up and the interpretation of protocol data heavily influence the outcome of the protocol studies. Most of the existing protocol analysis methods (Eckersley 1988; Stauffer and Ullman 1991; Lloyd et al. 1995; Purcell and Gero 1998; Atman et al. 2005; Jin and Chusilp 2006) are developed based on specific domains, individual design problems, or researcher's experience. It is hard to apply these protocol analysis methods into other practices. This protocol analysis method proposed in the present thesis targets to meet these challenges. Before establishing a more effective approach of protocol analysis, it is essential to analyze the requirements for conducting a protocol analysis experiment.

4.3 Requirements for Designing Protocol Analysis Experiments

The objective of studying protocol analysis in design is to understand designer's cognitive activities and track the changes of design activities during a design process. The experiment should not be heavily dependent on the used design problem, the field in which the problem is taken, or the person who analyzes the data. It should be designed objectively so that it can be used for analyzing general design phenomenon.

Before an experiment takes place, the researcher should clearly define the objective of the experiment. Without a clearly defined objective, the focus of the experiment is unclear and the data collected during the experiment may lack specific content. On the other hand, designer's thinking and cognitive activities are flexible and full of freedom during a design process. It is difficult to understand every detail of designers' activities. Different researchers may focus on different aspects of understanding designers' activities. So, the first step of designing the protocol analysis experiment is to set up an objective for the experiment.

Once the objective of the experiment has been specified, the researcher must identify all the details of the experiment to be conducted, including the selection of experimental participants, the design task, and the procedure of the experiment setting and the collection of the experimental data. The experimental participants should be able to solve the design problem and know one or two design methodologies, and have relevant design experience. The design task must be practical, solvable, easily understood and suitable for the participants with different levels. The procedure of the experiment should be designed in such a way that the participants' thinking and cognitive processes are not interfered during the data recording process. The data collection in protocol analysis experiment has mainly two types: concurrent and retrospective report. Both have their advantages and disadvantages as discussed earlier. The data collection methods must be modified so that the disadvantage can be counteracted.

After the experiment is conducted, the collected data should be transcribed into a written form. The verbal transcript (written form) should be then be segmented and encoded for further analysis of the designers' activities. The data can be first encoded into words, phrases, or sentences. The smaller the coded unit is, the more time and energy will be spent, but more accurate for quantification analysis. The coding scheme chosen should then be applied according to the aims of the analysis. The coding scheme is an important and critical part to analyze protocol data. It is used to transform the unstructured recorded data into structured representations of designer's cognitive activities. Then, the encoded data will be used for data analysis. Most of the current protocol studies devised the scheme according to specific design problems. If the design problem is changed, the scheme will also be changed. Those schemes cannot be extended for other applications. Thus, a flexible encoding scheme is essential for verbal protocol analysis. Reliability and accuracy of the coding scheme then has to be established.

Finally, the researcher can further analyze the results based on the encoded data. The data structured in each encoding category require summing, simply by adding up the frequency of occurrence noted in each category. The researcher should then analyze the data using appropriate statistical test, graphs etc. The form of analysis used is dependent upon the aims of the analysis, but typically involves transforming the words collected into numerical form in readiness for statistical analysis. In this way, the designers' cognitive activities in a design process can be represented using the numerical data. Then, the further analysis for quantification of designer's cognitive activities or validating a design theory can be conducted to match with the objective of the experiment.

In summary, the requirements for designing protocol analysis experiments are as follows.

1) The objective of the experiment should be defined before conducting the experiment.

2) The apparatus and the context of the experiment should be identified, including selection of experimental participants, design task, and procedure of the experiment.

3) A data collection method: concurrent, retrospective or a modified one need to be specified to ensure the accuracy of the data collection and not interfering participants' cognitive behaviors.

4) Data processing should be conducted, including transcription, segmentation and encoding; especially a flexible, accurate and reliable encoding scheme should be developed.

5) Further analysis need to be conducted from the encoded data to verify the objective of the experiment.

4.4 Design of the Experiment

The experimental design includes the specification of the objective of the experiment, the selection of the design problem, the subjects, and the procedure of setting up the experiment.

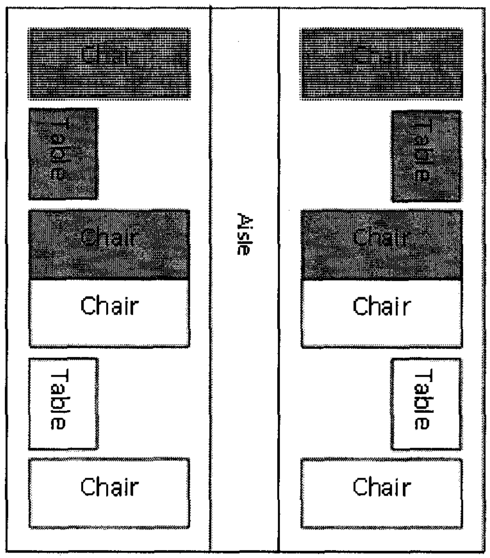
4.4.1 Objective

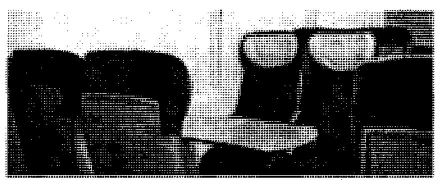
There are two objectives of conducting the protocol analysis experiment. First, the protocol data are used for evaluating the environment-based design methodology. The second objective is to investigate the factors leading designers to generate different concepts. The details of how the protocol data is used to evaluate environment-based design methodology are introduced in Chapter 5.

4.4.2 Design problem

Design problems should be selected based on their potential demands on different aspects of design skills. They should be practical, solvable, easily understood, and suitable for designers with different levels (Dorst and Cross 2001). The design problem used in this research is adapted from the research of Dorst and Cross (2001) because it is feasible, realistic, open-ended and challenging enough for the anticipated subjects in the present study. This design problem is to design a new litter-disposal system in a passenger compartment located in the trains of NS (Dutch Railways). The original description for this design problem can be found in Dorst and Cross (2001). The design problem was rephrased to be more easily understood by our subjects as shown below.

Design problem: to design a litter-disposal system for the passenger compartment in a railway train. This system should be convenient for the passengers to deposit garbage and meanwhile it is easy for the cleaners to collect the garbage. The structure of the passenger compartment is as follows.





You are asked to generate a design concept for the design problem above. You need to write down all your ideas, concepts and draw the sketches to illustrate your solutions in your design process.

4.4.3 Subjects

Subjects play an active role in the experiment of protocol analysis. The subjects should represent the population or group in which the research is interested. Moreover, a greater sample size for the subjects can give the experiment greater statistical power to find significant difference. However, in human related experiments, it is difficult to clearly give the best sample size for conducting an experiment. Researchers have to conduct experiments and evaluations with relatively low numbers of subjects because of time, expense or the limited availability of subjects with certain requirements (Wickens et al. 1998). Cross (2002) developed a general descriptive model of creative cognition in design from the comparisons of three exceptional designers using two retrospective interview studies and one protocol study. Stauffer and Ullman (1991) observed five mechanical engineers engaged in open-ended design problems and divided the designers' actions into 'operations' of short durations. Three designers were used by Gero and Mc Neil (1998) in their research to investigate the process of designing. Different designers have different creative abilities, but all designers use the same cognitive processes, which are what most of the design research is interested in.

In this research, the criteria for selecting the subjects include educational background, engineering design experience and language ability. A subject should have basic training in engineering design and understand what is expected in performing a design task. Meanwhile, the subjects should be able to express their thoughts in English reasonable well. In this experiment, seven graduate students with various cultural backgrounds and engineering experience (5-10 years) volunteered as the subjects. They were asked to solve a design problem and talk about their design processes. They all signed a consent form and a survey form for participating in the experiment. The consent form and the survey form can be found in Appendix 1 and Appendix 2 respectively.

4.4.4 Experiment set-up

The experiment has two sessions: design session and interview session. In the design session, the subjects worked alone on the design problem in a quiet room; in the interview session, the subjects were interviewed by the researcher to recall their design process and speak out their thoughts. In this experiment, three webcams were set up to record the entire process including audio and video information from different angles, as shown in Figure 4-1.

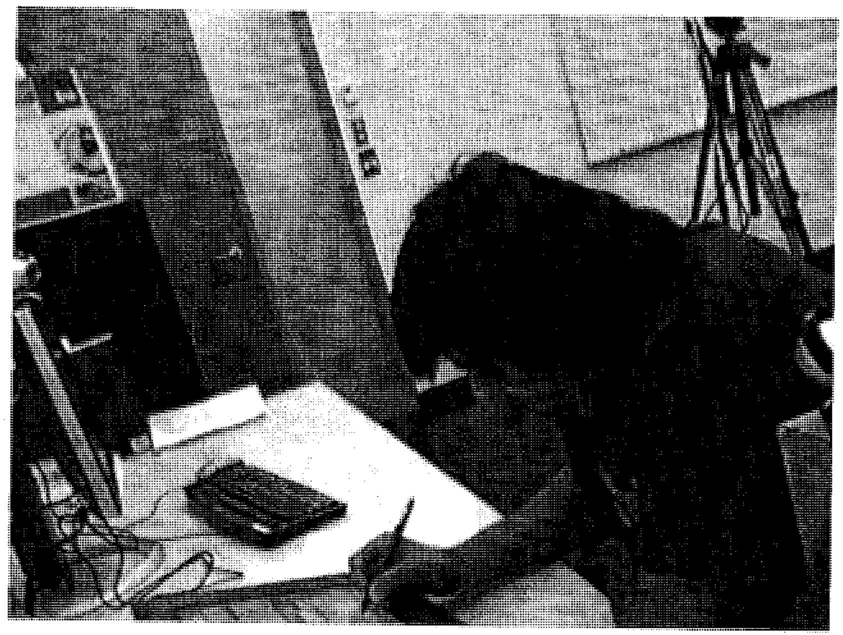


Figure 4-1 Experiment set-up.

In the design session, the researcher presented the design problem to the subjects and explained the procedure of the experiment to them. Then the subjects were required to draw and write anything they want to solve the design problem on a WACOM tablet screen using the tablet pen with the help of the sketching software of "Procreate Painter Classic". The tablet screen is shown in Figure 4-2. The "Procreate Painter Classic" software is a kind of tool to support designers to draw or write anything on the computer screen. The subjects can easily choose different brushes, colors, erasers, sizes and other tools to modify or draw their sketches. Before subjects began to solve the problem, they were given 5-10 minutes to use the tablet pen and the tablet screen to draw sketches in order to feel as if they were using pen and paper. The activities done on the tablet screen by subjects were recorded by the software of "My Screen Recorder". This software can record anything that subjects draw or write on the screen of the computer. The process of the subjects' drawing or writing can be completely recorded and tracked.

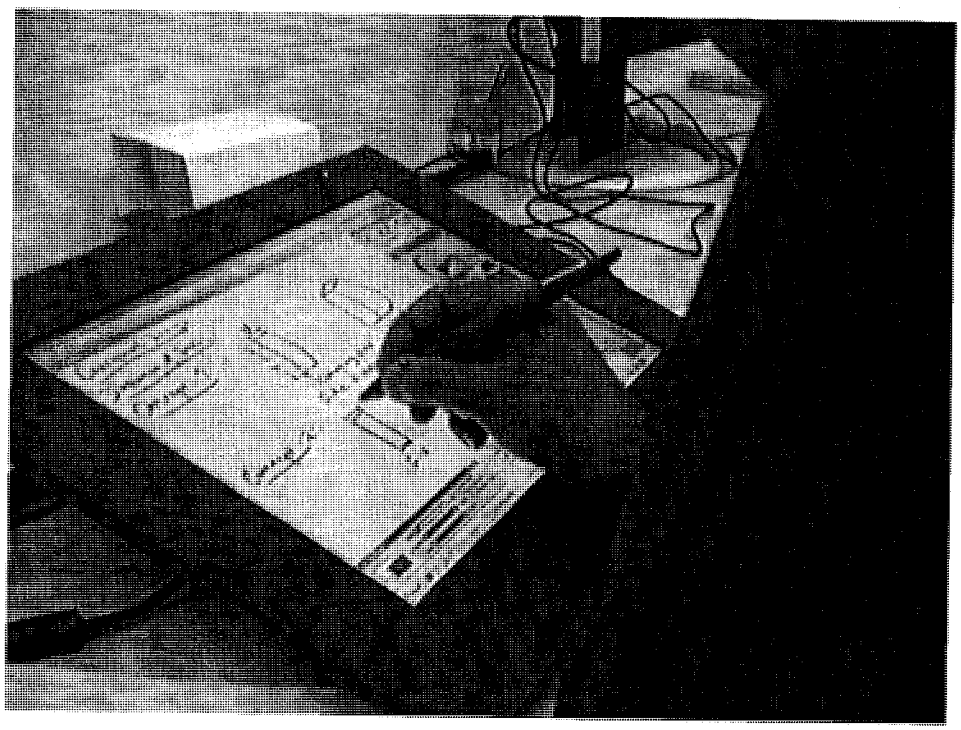
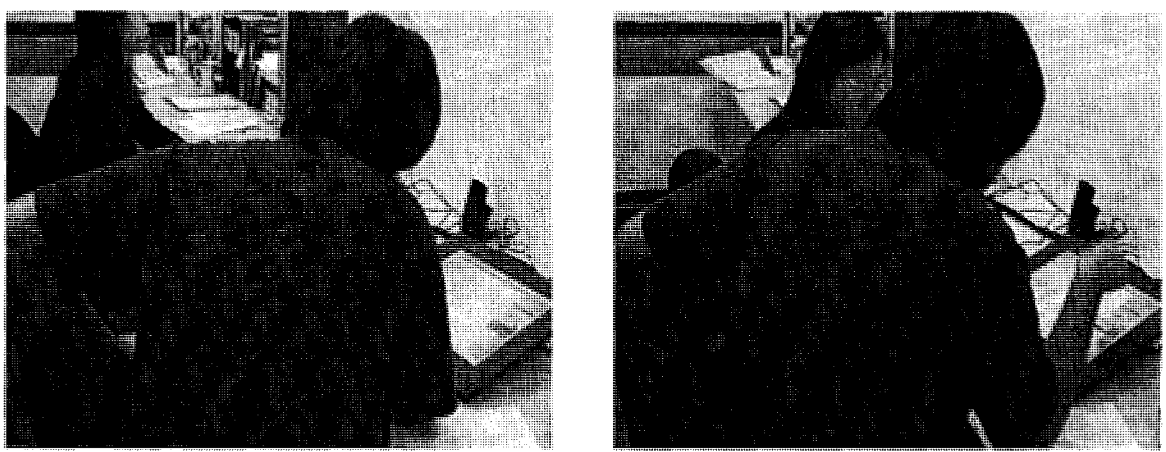


Figure 4-2 Tablet screen.

Subjects' actions and the screen activities were monitored by the researcher on another monitor at the same time, as shown in Figure 4-3 (a). By watching the subjects' activities from another monitor, the researcher can understand the subjects' general actions and intentions and then prepare a list of questions about the subjects' decision making process. At the same time, the researcher is ready to answer any question from the subjects during the design session.

In the interview session, the researcher asked the subjects to recall their design process based on the questions prepared during the design session. At the same time, the recorded audio, video and screen activities in the design session were shown to the subjects as memory cues to remind their thoughts. Then, the subjects' utterances were recorded and used for further analysis. The interview session is illustrated in Figure 4-3 (b).



(a) (b)

Figure 4-3 Design and interview sessions.

From the procedure of the experiment set-up, it can be seen that the subjects' thinking and cognitive process during the design session were not interfered and there was no additional mental workload on the subjects; in the interview session, the subjects were reminded of their thinking and cognitive process by asking questions and watching their videos of the design session. Therefore, the data recorded during the design session truly represents the subjects' cognitive activities of solving design problems. All the recorded data collected from the two sessions were then organized for data processing and analysis.

4.5 Data Collection

There are two major approaches in protocol analysis to collect protocol data: concurrent verbalization and retrospective verbal report. As mentioned earlier, both methods have their advantages and disadvantages. Concurrent reports have their advantages in tracking designers' thinking behaviors at any time in the design process, but some designers may not be capable of describing certain mental operations and talking aloud may inadvertently affect the thinking process. In retrospective reports, designers' thinking processes are not interfered, but designers might recall their design process partially and selectively. Considering the advantages and disadvantages of these two methods for collecting protocol data, the present research designed another method for data collection.

The experiment conduced in this research have two stages: design session and interview session. In the design session, the subjects worked alone on the design problem without any interference; in the interview session, the researcher showed the recorded video of the design session to the subjects and asked the subjects some questions summarized from the design session to lead the subjects to recall their thinking process. The subjects' talking and recalling their thinking process in the design session are recorded and organized for further data processing and analysis. So the data collected in this experiment is neither a concurrent report nor a retrospective one. The concurrent report could affect the subjects' thinking process and the retrospective report could make the subjects only partially or selectively recall their design process; both of the two types of the data collection cannot make the recorded data accurately and reliably. However, this experiment used the form of interviewing the subjects to recall their design process while leaving the subjects work alone on the design problem first so that the data collection used in this experiment is accurate and reliable.

4.6 Evaluation of Design Solutions

To understand and compare how the subjects perform in the design process, it is essential to evaluate the design solutions of the subjects. First, all related factors or environment components about this design problem are identified. There are train, compartment, cleaner/garbage collector, railways/user, manufacturer, passenger, and garbage. Then all relationships between these factors are analyzed. The relationships can be categorized as direct, indirect, negligible relationships. For example, passengers have direct relationships with garbage; passengers and cleaners have indirect relationships through garbage; the relationships between manufacturer and garbage can be ignored. The possible relationships between each environment components and the system are also analyzed. The final structure showing the relationships is illustrated in Figure 4-4. A line between two neighboring components represents a direct relationship. The two objects without a line between them have no relationships or have indirect relationships between each other.

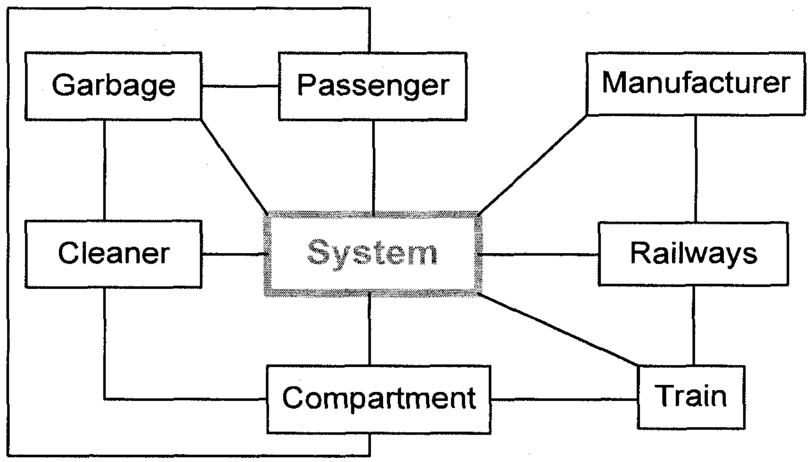


Figure 4-4 Product-environment structure of the design problem.

From the relation structure, the requirements for this design problem can be summarized as follows:

Product Requirements
R1: The system should be convenient for the passengers to deposit garbage; R2: The system should be easy for the cleaners to collect the garbage; R3: The system should fit the structure of the compartment; R4: The system is used in the train and should keep static when the train is moving; R5: The system should be acceptable for the railway company; R6: The system should be produced to fit the requirements of the manufacturer; R7: The system can contain different garbage deposited by the passenger.

Two assessors evaluated the results of the design solutions of the seven subjects. According to the importance of the product requirements, weighting factors are given for the above requirements as 0.2, 0.2, 0.2, 0.1, 0.1, 0.1, and 0.1 respectively. The design solutions are scored by reviewing the transcript, segmentation and encoding, as well as any writings or drawings by the subjects. The assessors give the highest score (10) if a requirement is satisfied well and the least score (1) if a requirement is not satisfied. It will be a good design if all requirements are well satisfied. A total score is given as $M_i = \sum_{j=1}^{7} w_j S_i^j$ (w_j is the weight for the j^{th} product requirement; S_i^j is the score of the j^{th} product requirement for the subject No.i. The average scores from the two assessors are used as the final results. The design solutions are ranked according to scores shown in Table 4-1. The scores shown in Table 4-1 can be used to evaluate the design solutions conducted by the subjects. A high score shows a better solution.

Table 4-1 Final score of the subjects' design solutions

	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**Total Score**
Subject 1	8.25	9.5	9.0	9.5	4.0	6.75	7.5	**8.125**
Subject 2	7.25	6.9	7.0	3.0	7.25	7.5	7.0	**6.705**
Subject 3	7.75	7.0	7.6	9.5	7.5	8.0	7.0	**7.67**
Subject 4	8.25	7.5	7.1	3.0	8.75	7.5	8.4	**7.335**
Subject 5	7.25	5.0	6.0	3.0	7.25	7.0	6.5	**6.025**
Subject 6	9.25	5.75	8.75	8.5	7.5	7.5	7.0	**7.8**
Subject 7	7.75	8.0	7.0	9.5	8.5	8.0	9.5	**8.1**

4.7 Data Processing and Analysis

After the experiment is conducted, the protocol data is collected and organized from the subjects' video, audio and screen-recording information, mainly from the interview session. The recorded information from the design session is taken as a reference for understanding the subjects' intentions and actions from their sketches, facial expressions and physical movements. The collected protocol data are then processed for transcription, segmentation, and encoding. The transcription is to transcribe the protocol data into written text documents. The segmentation is to divide the transcribed text into segments. Then the segments are encoded into different categories using the coding scheme. After encoding, the protocol data can be represented using different categories and diagrams. Then the subjects' cognitive activities can be further analyzed.

4.7.1 Transcription

Once the experiment is conducted, the first step is to transcribe all the words spoken by subjects during the interview session into text documents. The text documents may contain some vague and inconsistent information, so it is necessary to remove some unrelated information and add some annotations to explain their non-verbal intentions to make the transcript more consistent. It is also important to make sure the sequence of the transcribed data in a correct order that matches with the subjects' activities in the design session. There are three operators to do cross-checking to ensure the accuracy and consistency of the transcript and get the final formalized transcripts. Below is an example of the formalized transcript.

"……

Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table. It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats and tables (point to the sketches on the screen). This place (right under the seats) is not convenient for picking up by cleaners. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle.

……"

4.7.2 Segmentation

The objective of segmentation is to break the transcribed text into segments, which can be encoded with a coding scheme. As proposed by Zeng (2002), a design process is characterized by a series of design states and each design state is composed of environment components, product components and their relationships. As introduced in Chapter 3, a new state of design can be defined as the structure of the old environment (E_i) and the newly generated design concept (S_i), which is a partial design solution, shown in the following equation,

$$\oplus E_{i+1} = \oplus(E_i \cup S_i) = (\oplus E_i) \cup (\oplus S_i) \cup (E_i \otimes S_i) \cup (S_i \otimes E_i).$$

So the transcript, which represents designers' cognitive activities during the design process, can be divided into separate design states. The concept of design state is used in the experiment analysis as the basic unit for the segmentation of protocol data. The transcript example shown above is segmented into three parts as shown in Table 4-2.

Each segment represents a design state. Since a design state is composed of environment components, product components and their relationships, the difference between design states could be due to modifying, adding, or deleting environment components, generating or modifying product concepts, or modify the relationships between environment components and product concepts. Some protocol data describing designers' own thoughts have no relationship on environment components and their relationships and it is taken as meta-language. If necessary, the segmented design states can be merged to form other segmentation categories.

Table 4-2 Segmentation example

Segment i+1	Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table.
Segment i+2	It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats and tables (point to the sketches on the screen)
Segment i+3	This place (right under the seats) is not convenient for picking up by cleaners. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle.

4.7.3 Coding scheme

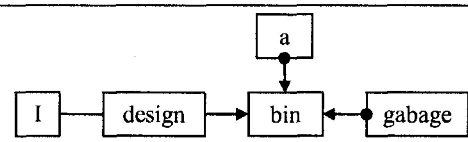
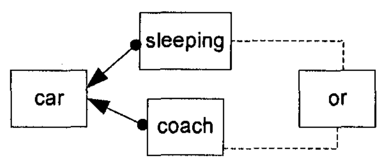
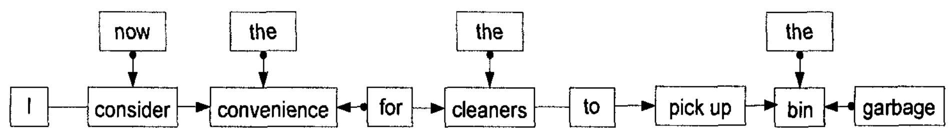
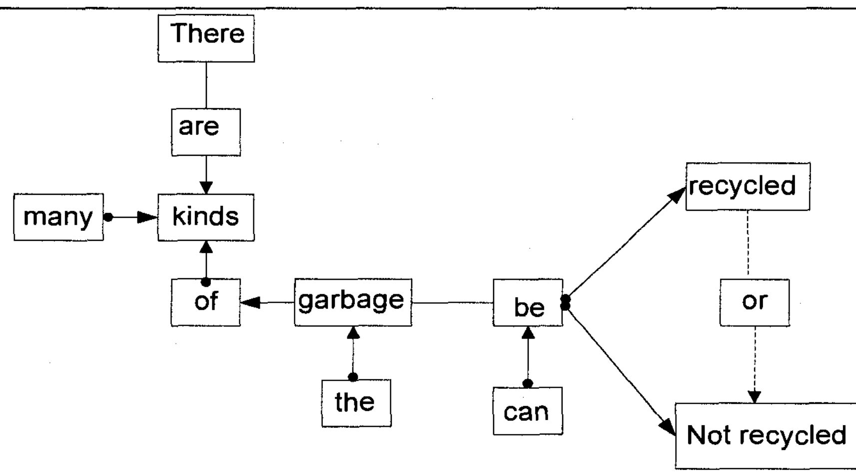
Encoding is an important and critical part to analyze subjects' protocol data. Design process proceeds with the evolution of design states. A design state (DS) can be decomposed into the structure of the product, $\oplus S_i$, the structure of the environment, $\oplus E_i$, and their relationships, $B_i=(E_i \otimes S_i) \cup (S_i \otimes E_i)$. An environment may contain several environment components, represented as $E_i = \sum_j e_j$. R(a,b) is used to represent the relationships between two objects and it can be applied to multiple object relationships. According to the definition of the encoding scheme, the segmented transcript in Table 4-2 is encoded shown in Table 4-3. The complete encoding of subject 1 can be found in Appendix 1. It should be noted that the encodings of the seven subjects based on the design states have been checked by the author three times to ensure the consistency of the encoding.

Table 4-3 Encoding example

	Environment	**Product**	**Relationship**
DS i+1	e_1=cleaner e_2=table e_3=aisle $e_4=S_{i-1}$=a garbage bin	s_i=the location of the garbage bin: to put the garbage bin under the table $S_i=S_{i-1} \cup s_i$=the location of the garbage bin is specified to be under the table	$b_1=R(e_1, e_4)$= cleaners pick up the garbage bin; $b2=R(e_1, e_3)$=cleaners walk along the aisle; $b3=R(e_2, e_4)$= garbage bin is put under the table;
DS i+2	e_1=passenger e_2=seat e_3=table $e_4=S_i$=the location of the garbage bin is specified to be under the table	s_{i+1}=the location of the garbage bin: to put the garbage bin under the seats $S_{i+1}=S_i \cup s_{i+1}$=the location of the garbage bin is specified to be under the seats	$b_1=R(e_1, e_4)$= the location of putting garbage bin under the table affects the movement of passenger's legs; $b_2=R(e_2, e_3, e_4)$= the only place is under the seats considering seats and tables.
DS i+3	e_1=cleaner e_2=seat e_3=aisle $e_4=S_{i+1}$=the location of the garbage bin is specified to be under the seats	s_{i+2}=the location of the garbage bin: to put the garbage bin along the side of the seats close to the aisle $S_{i+2}=S_{i+1} \cup s_{i+2}$=the location of the garbage bin is specified to be along the side of the seats close to the aisle	$b_1=R(e_1, e_4)$=the location of putting garbage bin under the seats is not convenient for cleaners to pick up; $b_2=R(e_2, e_3, e_4)$= considering putting the garbage bin along the side of seats close to the aisle

On the other hand, recursive object model (ROM) (Zeng 2007), is used to capture the relationships implied in the protocol data of each design state. The segmented transcript represents a design state; the design state is composed of several sentences. ROM is a graphic language representing all the linguistic elements in technical English, derived from axiomatic theory of design modeling. Section 3.3 has briefly introduced the graphic symbols of ROM shown in Table 3-1. Two objects and three relations are used to represent the objects and the relationships implied in language elements. The two objects are represented as symbols of object and compound object; the three relations are constraint relation, connection relation, and predicate relation. They can be used to represent environment components and their relations implied in the protocol data. Table 4-4 shows several examples of ROM diagrams. ROM can be used to collect, organize, and interpret protocol data, especially analyze the characteristics by inferring from multiple object relationships. Therefore, the protocol data in each design state can be further encoded into ROM diagrams to represent the linguistic information embedded in the protocol data. The ROM diagrams can be used to quantify designers' cognitive activities. Some work has been done to quantify designers' mental stress in their design processes using ROM diagrams (Zhu et al. 2007). Figure 4-5 shows the quantification of designers' mental stress. The seven subjects' mental stress is sorted from low to high level in the following order: 2, 5, 1, 7, 6, 4 and 3.

Table 4-4 Examples of ROM diagrams.

Natural Language	ROM diagram
I design a garbage bin.	
coach car or sleeping car.	
Now I consider the convenience for the cleaner to pick up the garbage bin.	
There are many kinds of garbage. The garbage can be recycled or not recycled.	

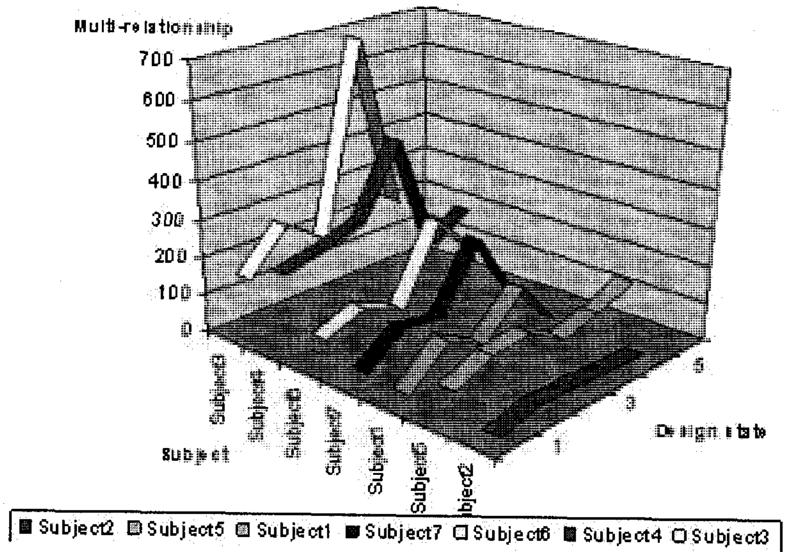


Figure 4-5 Quantification of designers' mental stress (Zeng 2007).

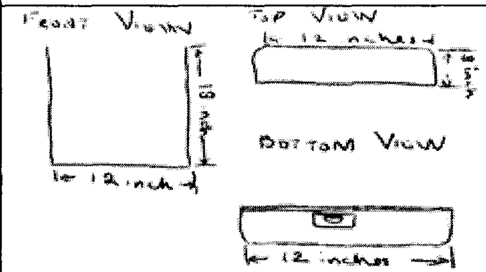
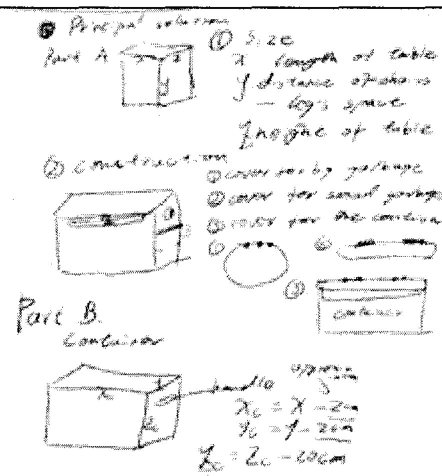
4.8 Results and Discussions

The design of the litter-disposal system can be decomposed into four parts: 1) design of the location of the system, 2) design of the structure of the system including material, cost, shape, size, etc, 3) design of the collection of the garbage from the system, and 4) design of depositing garbage into the system. The seven subjects generated different concepts on these four parts. The four design concepts are the key concepts of completing the design solutions. This section chooses subject 2 and subject 4 to compare the differences between their key design concepts and identify the strategies that creative designers take to generate good designs. First, the differences of the design concepts between subject 2 and subject 4 are compared. Then, the design processes of subject 2 and subject 4 are compared to examine the three routes leading to different designs proposed in Section 2.2.3.

4.8.1 Analysis on the design concepts

The design concepts and the final concept sketches of subject 2 and subject 4 are listed in Table 4-5.

Table 4-5 Design concepts of subject 2 and subject 4

	Design of System Location	**Design of System Structure**	**Design of Garbage Collection**	**Design of Garbage Depositing**	**Final concept sketch**
S2	Underneath the window fixed with the wall	A bin with lever or latch on the bottom	Collecting garbage in a plastic bag from the bottom the bottom of the bin by pushing the latch	No cover, just putting garbage in the bin	
S4	Under the table	A bin with a long and narrow hole on two sides and a big hole on the front including size and material	Collecting garbage from the container in the bin	Pushing the cover of the bin	

The protocol data of the subjects can illustrate how these design concepts were generated by the subjects. The protocol data has been encoded into a series of design states. In each design state, environment components and their relationships were identified and encoded using the symbols showing in Section 4.7.3. It is assumed that creative designers consider more environment components and analyze deeper relationships between environment components in generating a design concept. The number of environment components and the number of relationships that subject 2 and subject 4 considered to deliver the four key design concepts are counted and compared in Table 4-6. In this table, design concept 1, design concept 2, design concept 3, design concept 4 represent the design of system location, design of system structure, design of garbage collection, and design of garbage depositing respectively; NE and NR represent the number of environment components in generating each design concept and the number of relationships between environment components respectively; NT represents the total number of environment components and the relationships between environment components.

Table 4-6 Comparisons of design concepts between subject 2 and subject 4

	Design Concept 1			**Design Concept 2**			**Design Concept 3**			**Design Concept 4**		
	NE	**NR**	**NT**	**NE**	**NR**	**NT**	**NE**	**NR**	**NT**	**NE**	**NR**	**NT**
S2	10	4	14	7	4	11	2	1	3	7	3	10
S4	13	5	18	14	10	24	30	17	47	7	8	15

Figure 4-6 shows the number of environment components identified by subject 2 and subject 4 in generating each design concept. It can be seen that subject 4 considered more environment components in generating design concept 1 to 3 than subject 2. For the design concept 4, the two subjects considered the same number of environment components, but subject 4 analyzed more relationships among the environment components than subject 2, as shown in Figure 4-7. Figure 4-7 also illustrates subject 4 analyzed more relationships among environment components than subject 2 in generating all four design concepts. Figure 4-8 shows subject 4 has a higher total number of environment components and their relationships than subject 2. From these comparisons, it can be found that subject 4 considered more environment components, deeper relationships between environment components than subject 2. Table 4-1 shows the design solution generated by subject 4 is better than the one generated by subject 2. Relatively, subject 4 is a more creative designer compared with subject 2.

When designers think to generate a design concept, they consider as much as possible environment components and identify the relationships between environment components. However, due to the differences of designers' knowledge and experience, their cognitive abilities in identifying the sufficient environment components and in analyzing the relationships between environment components are different. A creative designer must have a higher mental stress level to consider more environment components and analyze deeper relationships in order to deliver a better solution. This matches with fact that the mental stress level of subject 4 is higher than that of subject 2, as shown in Figure 4-5.

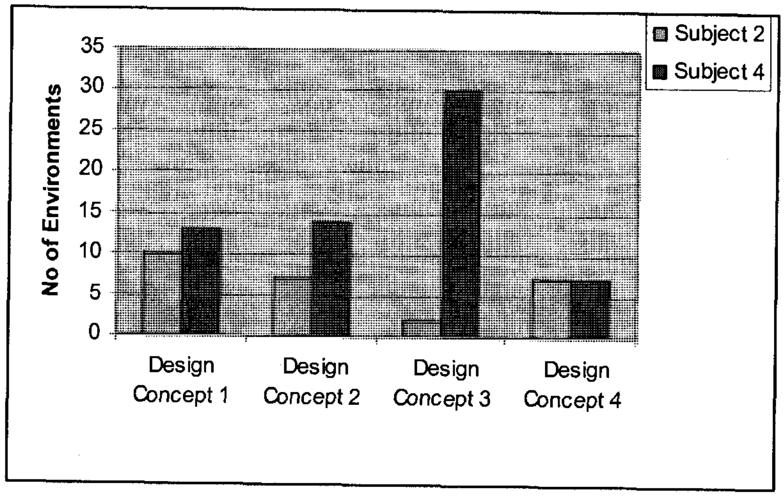


Figure 4-6 Comparison of number of environment components

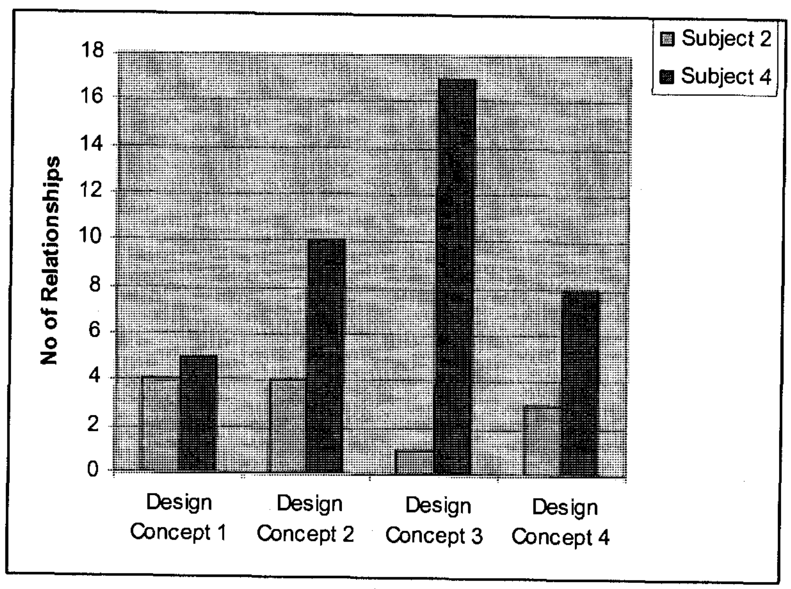


Figure 4-7 Comparison of number of relationship components

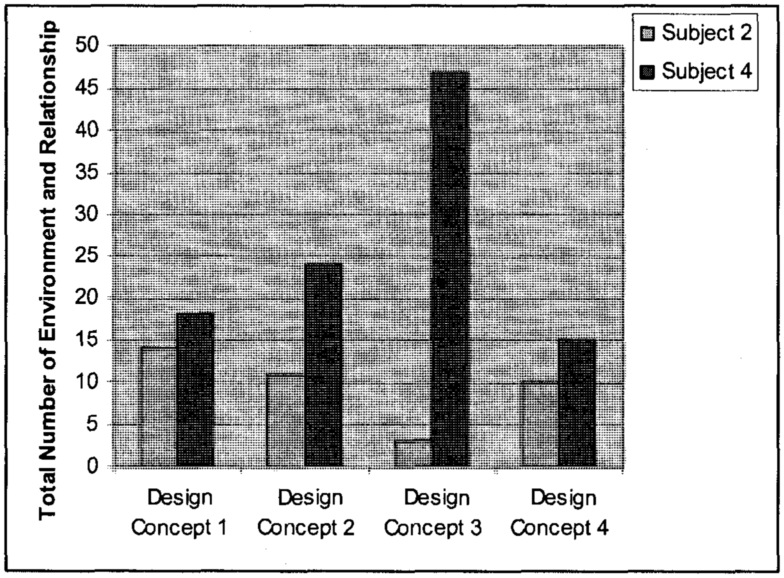


Figure 4-8 Comparison of total number of environment and relationships

4.8.2 Analysis on the routes leading to different designs

The seven subjects started solving the design problem from different perspectives and formulated different requirements for the design problem. Some of the subjects applied design methodologies to formulate the problems and generated the first concepts. Some subjects started thinking of the location of the system in the compartment; some first thought about the structure of the bin; and others think about the material of the bin first. With different formulation of the design problem, they generate different concepts; even for the same formulation of the design problem, for example, designing the location of the garbage bin, subject 3 thought to put the garbage bin under the table, but subject 6 thought to put under the chairs. All the subjects thought to design the location of the system, the structure of the system, the collection of the garbage from the system, and the depositing of the garbage into the system, but they followed different sequences to conduct these four design tasks, which also make their final design differently. The subjects in this experiment have different background in culture, education and experiences. Their design knowledge is different, so are their design concepts, even considering the same design task. So, it can be seen that different subjects may formulate the design problem differently, use different sequence of decomposition of the design problem and generate different concepts based on their design knowledge. Subject 2 and subject 4 have different scores for their design solutions as shown in Table 4-1. These two subjects are used to compare their differences and similarities in their design processes, and illustrate how they formulate the design problem differently, use different sequence of decomposition of design problem and apply different design knowledge to generate concepts.

1) Formulating the design problem differently

Subject 2 first determined to design a bin for this design problem. Then, he identified the environment components: train, cleaner, passenger and figured out the requirements for the design problem, "...... And the garbage bin is there (in the train). And I want to design the garbage bin that is easy for people (passenger) and easy for garbage collector." Based on the requirements, he generated the concept for the structure of the bin, "......My garbage bin that I suggested opens from the underneath (bottom)." Based on this concept, he continued to design the other concepts until he finished the design. Subject 4 first read the description of the design problem and figured out to design a dustbin for a train. Then, he identified the related environment components:

manufacturing company, train, passenger, cleaner, and railway company and determine the next step, "...... Then I try to figure out the requirements from each environment. It is also the relationship between the product and environment." He analyzed that the relationship between the manufacturing company and the railway company; the relationship between the train and the bin; the relationship between passenger and collector and the relationship between the manufacturing company and the system. From analyzing the relationship between the manufacturing company and the bin, he thought the bin should be like a box as he recalled, "...... So I have the rough concept which should be like a box. It is the first concept of design." Then he continued to design other concepts based on this concept. The differences of the formulation of the design problem between the two subjects are summarized as Table 4-7.

Table 4-7 Comparisons of first concept between subject 2 and subject 4

	Environment components	**Relationships**	**First concept**
S2	Train Cleaner Passenger	That is easy for people (passenger) and easy for garbage collector.	My garbage bin that I suggested opens from the underneath (bottom)
S4	Manufacturing company Train Passenger Cleaner Railway company	The relationship between the manufacturing company and the railway company; The relationship between the train and the bin; The relationship between passenger and collector The relationship between the manufacturing company and the system.	The bin should be like a box

From the formulations of the design problem of the two subjects above, it can be found that different designer may formulate the design problem differently. Subject 2 only considered three environment components and generally thought about the relationships between them. Subject 4 identified five environment components and carefully analyzed their relationships. The two subjects started their design at different points. Their first concepts are different and so their final design.

2) Changing the sequence of decomposition of design problem

Both subject 2 and subject 4 thought that the litter-disposal system should be a bin. Then, they analyzed the requirements for designing a bin. Subject 2 first got the concept that the bin should open from the bottom, then designed a lever or latch used to open the bottom of the bin, and thought to put a plastic bag in the bin, then identified the location of the bin to be put under the window and fix the bin with the wall, and the bin has no cover, and finally, he specified the size of the bin. Subject 4 first decided the shape of the bin, the size of the bin, then determined the location of the bin, designed the form of the hole and the cover of the bin, added a container in the bin, decided the material for the bin, added a handle for the container, and finally he estimated the cost of the bin. Although the two subjects both considered the same tasks: location of the bin, collection of the garbage, depositing garbage and the structure of the bin, they followed different sequence for decomposing the design problem into small tasks. Moreover, for each task, they generated different concepts. So their final design concepts are quite different.

3) Applying design knowledge to generate design concepts

Both subjects considered how to use the bin to deposit garbage. Subject 2 didn't design a cover for the bin and thought it was convenient for the passengers to directly deposit garbage into the bin from the top. Subject 4 designed two long and narrow holes on the sides of the bin for depositing small garbage and a big hole in the front for depositing big garbage; also he designed covers for the holes. The two subjects generate their concepts and evaluate them based on their knowledge for understanding the relationship between passenger, garbage and the bin. Subject 4 thought that garbage has different categories (big and small) and the garbage doesn't smell good and look good when it is visible for them. The passengers can easily and comfortably deposit the garbage simply by pushing the cover. Subject 2 didn't think about different garbage in their design. So, the design concepts of the two designers are different for designing the concept to depositing garbage into the bin. It can be seen that for the same requirements, the different subjects give different concept since their knowledge is different for generation and evaluation.

The two subjects' design processes have been compared by examining three routes: formulating the design problem differently, changing the sequences of decomposing the design problem, and extending knowledge for generating concepts for the same requirements. It can be found that these routes can affect the designers' design behavior and their final design concepts. On the other hand, these routes can be applied to assist designers to get new design solutions, which may lead to creative design. Chapter 6 will use a computer simulated design model to simulate these three routes for generating different design solutions in a virtual environment.

4.9 Comparisons

4.9.1 Comparison to the research of Dorst and Cross

The design problem used in this experiment was originally adapted from the research of Dorst and Cross (2001). In their research, nine experienced designers were asked to think-aloud as they were solving the design problem. Their protocol data were reorganized and narrated from the perspective of the authors to determine the motivation and attitude of the designers towards the test situation and their own design. The authors were interested in the overall "quality" of the resulting design concepts produced by the designers. Then, from the protocol data, some aspects of creativity in design related to the formulation of the design problem and to the concept of originality are observed and summarized. The observations from the protocol data are also used to validate the model of creative design proposed by Maher et al. (1996). There are no details of describing the transcription, segmentation and encoding of the protocol data. This research mainly focuses on qualitatively observing the protocol data.

The research presented in this thesis used the same design problem and redesigned the experiment of protocol analysis from the perspective of quantitatively analyzing the protocol data to further understand designers' cognitive activities. In this present research, designers' activities had gone through two sessions: design session and interview session. In the design session, the designers concentrated to solve the design problem without any interference. In the interview session, the designers were interviewed to recall their thinking processes and problem-solving behaviors during the design session while watching the videos of their design session. The original narration from the designers about their thinking process in the interview session was analyzed to quantify designer's cognitive activities through transcription, segmentation and encoding. The segmentation of the protocol data is based on the concept of design states. A design process is composed of a series of design states, which are defined by the partial design problem requirements and partial design solutions. The design process evolves with the evolution of the design states. So, it is interesting to see that the model of creative design used in Dorst and Cross's research, which stated that "the problem space and the solution space co-evolve together, with interchange of information between the two spaces" is implied in the concept of design states of this present research.

Designers' thinking and cognitive processes can be described by the designers using natural language in the form of "think-aloud" or the retrospective report. However due to the laborious work of organizing the verbal protocol data and the huge information contained in the language description, it is difficult to find a reliable and independent coding scheme to transform the unstructured verbal protocol data into a structured form, which can be used for further quantification analysis of designers' cognitive activities. In this present study, the coding scheme is developed using the concept of design states and the recursive object model based on the axiomatic theory of design modeling. The segmented protocol data is first encoded based on the symbols representing design states. From the encoded data, it is easy to identify the environment components, product components and their relationships implied in the design states. ROM provides a powerful tool to analyze the linguistic elements in the verbal protocol data. From the ROM diagrams, this present study can easily quantify the changes of the cognitive activities of the designers. Therefore, the protocol analysis method proposed in this research can be taken as an in-depth study of the protocol analysis to quantify designer's cognitive activities. By analyzing designers' cognitive activities, some creative routes and guidelines can be recommended for assisting designers to deliver successful and innovative design solutions.

In summary, the differences between the present research and the research conducted by Dorst and Cross lie in five aspects.

1) The original design problem is the same, but this present research modified the design problem to make it more understandable for the subjects.

2) The research objective is different. The objective of Dorst and Cross' research is to validate the observations about the aspects of creativity in design from the protocol data with the model of creative design of Maher et al (Maher et al. 1996). The objective of the present research is to develop an effective protocol analysis method and use the protocol data to validate environment-based design as a descriptive design model and identify factors leading to creative design.

3) In the design session of the Dorst and Cross' research, the designers were requested to think aloud as they were solving the design problem. In the design session of the present research, the designers were left alone to solve the design problems while their design activities were monitored and recorded.

4) The methods of collecting the protocol data are different. Dorst and Cross collected the verbal data that the designers talked in the design session and

determined the motivation and attitude of the designers towards their test situations and their own designs through a brief interview. In the present research, the protocol data is collected from what the designers answered the questions in the interview session.

5) In the research of Dorst and Cross, the protocol data is collected, but it is not further processed and analyzed. There is no introduction about the segmentation and the encoding. The conclusions are made based on the evaluations of the overall quality of the designers' design concepts and the observations of the protocol data. The present research further analyzed the protocol data through transcription, segmentation and encoding. The segmentation is made based on the concept of design state. The design state defines the basic unit of segmenting the protocol data and provides the flexibility of segmenting the protocol data into other categories. The coding scheme is based on the identification of the components and the relationships implied in the design states and the linguistic analysis using recursive object model. The segmentation method and the coding scheme provide the opportunity to further quantify designers' cognitive activities and develop the cognitive model of the design process.

4.9.2 Comparison to other protocol studies

Since 1980s, protocol analysis has been greatly used in investigating the process of designing and in understanding how designers design (Eckersley 1988; Stauffer and Ullman 1991; Lloyd et al. 1995; Purcell and Gero 1998; Atman et al. 2005; Jin and Chusilp 2006). Some representative work of protocol studies in design (Gero and Mc

Neill 1998; Suwa et al. 1998; Atman et al. 1999; Akin and Moustapha 2004; Jin and Chusilp 2006) are chosen to compare with the protocol study presented in this thesis. In 1998, Gero and Mc Neil (1998) developed and applied a methodology that uses protocol studies of designers engaged in design to investigate the process of designing. In 1998, Suwa et al. devised a new scheme for coding designers' cognitive actions from video/audio design protocols. In 1999, Atman et al. compared freshman and senior students to find their differences and similarities in the design process when working on the same design problem. In 2004, Akin and Moustapha sought a better understanding of the specific cognitive processes contributing to architectural massing from six architects' protocol sessions. In 2005, Atman et al. reported the results of an in-depth study of engineering student approaches to open-ended design problems based on the verbal protocols collected from 61 senior (fourth year) engineering students and 32 freshman (first year) engineering students as they worked on two design problems. In 2006, Jin and Chusilp proposed a framework to study mental iteration in different design situations to understand the repetition of cognitive activities occurring in designers' thinking process. Next, these protocol studies are compared with the protocol analysis method presented in the present thesis. As discussed earlier about the requirements of designing the experiment of protocol analysis, these protocol studies are compared from the aspects of the objective of the experiment, the experiment set-up, data collection methods, data processing and data analysis. These comparisons are shown in Table 4-8.

Table 4-8 The comparisons of the protocol studies

		Gero & McNeil	Suwa et al	Akin & Moustapha	Atman et al	Jin & Chusilp	The present study
Objective		To develop methods to articulate different aspects of the behaviour of individual designers and distinguish the designing behaviours of different designers	To devise a new scheme for coding designers' cognitive actions from audio/video protocols	To seek a better understanding of the specific cognitive processes contributing to massing	To compare freshman and senior to find their difference and similarities in the design	To use protocol data to evaluate and revise the proposed cognitive activity model of conceptual design and then investigate the process of mental iteration with regard to the types of design problem and constraint conditions	To find factors leading to creative design and evaluate environment-based design
Experiment set-up	**Design problem**	Three episodes: 1) to design part of an interface system; 2) to design an industrial controller; 3) to design another part of the overall system being designed in the first design episode.	To design an art museum in a given site	To design the three-dimensional massing configuration of a dormitory building on the Carnegie Mellon campus	To design a playground for a fictitious neighborhood.	1) creative design problem: self-powered personal transporter on snow; 2) routine design problem: power transmission system.	To design a litter-disposal system for the railway train.
	Subjects	1 PhD student in EE & 1 graduate in CS	1 practising architect	6 architects	26 freshman and 24 senior engineering students	16 subjects (15 graduate students+1 senior)	7 graduate students
	Procedure	The PhD student took episodes 1&2; 1 graduate took episode 3. The designers verbalized their thoughts during the design episodes and are video taped.	Participants worked on the task for 45 minutes while sketching on sheets of tracing paper. Their sketching activities were videotaped.	6 architects designed the three dimensional massing model. Each session lasted two hours on the average, was recorded on videotape and was followed by a brief post-experiment questionnaire.	The subjects were given up to 3 hours to read the design problem, solve it out loud. The protocols were audio and video taped.	16 subjects were equally divided into two groups. Additional constraints are imposed in group 2. Each subject worked on two design problems.	The subjects were left alone to work on the design problem and then interviewed to recall their design process.
Data collection		Concurrent verbal report	Retrospective report	Retrospective report	Concurrent verbal report	Concurrent verbal report	Retrospective report by interviewing.
Data processing	**Transcription**	Each designer's speech was transcribed and time coded.	Reports were transcribed.	The protocol sessions were transcribed into verbal expressions, drawing actions, or their combinations.	The tapes from the experimental sessions were transcribed.	The verbal protocol recorded from the design sessions was transcribed.	Subjects' talking in the interview session is transcribed.
	Segmentation	Segment the transcripts based on designer's actions or intentions	The protocols were divided based on the subject's intention.	The protocols were divided into a series of moves.	The transcripts were segmented into units of text. Each segment represents one idea.	The transcript was divided into segments which match with the corresponding cognitive activity.	The transcripts are segmented according to design states.
	Encoding	Encoding the segmented data into problem domain, micro strategy and macro strategy.	Each segment is coded into four categories: physical, perceptual, functional and conceptual.	The moves were categorized and color-coded according to the activity to which they contributed and their type.	The segments are coded based on design step, information processed, activity code, and object.	The coding scheme is designed to represent four key cognitive activities; the number of loops in each type of interaction looping is counted.	Design states and recursive object model are used to encode the protocol data.
Data analysis		Further results are exploded using graphical and filtering techniques.	Frequencies and correlations between actions were observed.	Observations and comparisons	MacSHAPA and statistical technique are used for data analysis.	Statistical technique is used for data analysis.	Further results can be obtained using statistical methods.

From Table 4-8, it can be seen that these protocol studies attempted to study designers' cognitive activities from different perspectives. The objectives of these protocol studies are different. The design problems, the number of designers, and the experiment set-up are also different. The protocol data is collected from the designers' utterance either in the design session or in the retrospective session. Then, the protocol data is further processed through transcription, segmentation and encoding. The big distinction among these protocol studies is the coding scheme. The coding scheme directly decides the categories that the protocol data belongs to. Further analysis and observations about designers' cognitive activities are based on the categories developed in the coding scheme. Gero and McNeil (1998) developed a coding scheme based on the problem domain, micro strategy and macro strategy. Suwa et al (1998) devised a scheme for coding designers' cognitive actions based on four cognitive levels: physical, perceptual, functional and conceptual. Akin and Moustapha (2004) categorized and color-coded a series of moves according to the activity to which they contributed (massing, planning, site analysis, program review, and design structure) and their type (analysis, decision, and evaluation). Atman et al (2005) coded the segmented protocols based on four variables: design step, activity, information processed, and object. Jin and Chusilp (2006) designed the coding scheme based on the cognitive activities (analyze problem, generate, compose and evaluate) and the iteration loop (problem redefinition, idea stimulation, concept reuse loop, analyze problem, generate, compose, and evaluate).

Most of the current protocol studies devised the coding schemes according to specific design problems. If the design problem is changed, the coding schemes need to be changed accordingly. Those coding schemes cannot be extended for other applications. It can be also found that these protocol studies used their own coding schemes for reaching their research objectives, which makes the comparisons between studies difficult. Moreover, identifying the categories and extracting the information from the protocols based on the coding scheme is mostly a manual process. Furthermore, the encoding process has to be repeated when the categories are changed, added, or deleted. In addition, the protocol analysis requires a tiresome and daunting amount of effort with an increase in the number of subjects and an increase in the length of the task. All these situations require a flexible coding scheme to accommodate the problems.

The coding scheme developed in this present research is based on the concept of design states and the recursive object model derived from axiomatic theory of design modeling. The protocol data is first segmented based on the concept of design states, and then the environment components, product components and their relationships are identified. Each identified design state may contain one or more sentences. All the design states can be represented by the ROM diagrams. Then, the ROM diagrams can be used to further collect, organize, interpret protocol data, and especially analyze the characteristics by inferring from multiple object relationships. A software system, ROMA, has been developed to support the transformation of natural English statements into ROM diagrams (Chen et al. 2007). The number of components in each design state can be easily and conveniently counted for qualitative and quantitative analysis. Since the design state is the basic unit of segmenting the protocol data, more design states can be aggregated and merged to form other categories according to the research being studied. The relationships among components in the design states can be represented in the ROM diagrams. Hence, the coding scheme developed in this present research can provide a flexible coding scheme for facilitating the research of understanding designers' cognitive activities. It can be also applied to other design problems for further studies.

4.10 Summary

In this present research, a product-environment-based protocol analysis method has been proposed based on the requirements analysis of designing the protocol analysis experiments (Yao and Zeng 2007b). The objective of the protocol analysis is to use the protocol data to evaluate the environment-based design methodology and investigate the factors leading designers to generate different concepts. The design problem in this experiment is to design a litter-disposal system for a railway train; this problem is feasible, realistic and challenging enough for the participants in this experiment. The participants for the experiment are seven graduate students who are selected based on their educational background, cultural difference and design experience. The experiment has two stages: design session and interview session. In the design session, the subjects worked alone on the design problem without any interference; in the interview session, the researcher showed the recorded video of the design session to the subjects and asked the subjects some questions summarized from the design session to lead the subjects to recall their thinking process. The subjects' talking and recalling their thinking process in the design session were recorded and organized for further data processing and analysis. After the experiment is conducted, the protocol data collected in the interview session are first transcribed by three operators through cross-examinations to ensure the accuracy and consistency. Then the protocol data are segmented based on the design states which reflect the nature and characteristics of the evolution of the design process. The coding scheme is developed using design states and recursive objective model derived from the axiomatic theory of design modeling. The encoded data represented in the ROM diagrams can be used to collect, organize, and interpret protocol data, especially analyze the characteristics by inferring from multiple object relationships.

The developed protocol analysis method has a few benefits.

1) The experiment is set-up in a way that completely and accurately record designers' design actions and cognitive activities, but minimize the interference to the designers' participation.

2) The data collected in this experiment is neither a concurrent report nor a retrospective one. The concurrent report could affect the designers' thinking process and the retrospective report could make the designers only partially or selectively recall their design process; both of the two types of the data collection cannot make the recorded data accurately and reliably. However, this experiment used the form of interviewing the designers to recall their design process while leaving the designers work alone on the design problem first so that the data collection used in this experiment would be accurate and reliable.

3) The coding scheme developed in this experiment is flexible, accurate and reliable. The encoded data is suitable for qualitative and quantitative analysis of designers' cognitive activities. It can be applied to the protocol data in other design problems and other domains.

Therefore, the protocol analysis method proposed in this research can be used for understanding general design activities and verifying existing design theories. The protocol analysis method is designed targeting general design problems, so it can also be applied in understanding other aspects of design activities and studying human cognitive activities in other domains.

Chapter 5
Evaluation of Environment Based Design Using Protocol Analysis

This chapter aims to use the protocol data in Chapter 4 to evaluate a new design methodology - Environment-Based Design (EBD) as a descriptive model of the design process. The protocol data is used to evaluate the process flow of EBD and the four main theorems behind the EBD methodology. The four theorems are 1) theorem of recursive logic of design, 2) theorem of source of product requirements, 3) theorem of dynamic structure of design problem, and 4) theorem of design driving force. Section 5.1 introduces the problem to be investigated. Section 5.2 describes an example of the protocol data. Section 5.3 gives the results and discussions. Finally conclusions are summarized in Section 5.4.

5.1 Introduction

A big challenge faced by the effort of developing effective design methodologies lies in two contrasting facts. On the one hand, design is a creative act; the freedom and the flexibility for exploring various avenues to achieve design goals appear to be critical for designers. Some attempts have been made in studying design creativity in the design process. Dorst and Cross (2001) indicated that creative design is a co-evolution process that looks for problem and solution at the same time. Akin and Akin (1998) concluded that it is not feasible to search for a unifying theory of the creative process because creativity is domain dependent after studying the creativity in puzzles, inventions and designs. Using the design of microprogramming as an example, Dasgupta (1994) points out that inventing is a goal-directed yet opportunistic act; thus the design agent's freedom and capacity to use his knowledge contribute significantly to the design creativity. From the cognitive point of view, Wharton (1999) characterized creativity as a focused mental process in which "we are not making something from nothing; rather, we are taking various existent elements and modifying them such that they interact in a new way". On the other hand, any design methodology implies a set of well structured logical steps for solving a design problem. During the past several decades, a variety of design methodology has been developed, such as systematic design methodology (Pahl and Beitz 1988), TRIZ (Altshuller 1984), axiomatic design (Suh 1990), decision-based design (Allan and Mistree 1997), artificial intelligence-based design (Gero 2000), etc. These design methodologies are prescriptive in that designers must follow a series of structured procedures to deliver a design solution. These structured procedures could add rigidity to the designer's thinking process. Thus, they have not been widely accepted in general design practices. This contradiction between flexibility and structure is made even more complicated by an intrinsic nature of design: design solutions must pass an evaluation defined by design knowledge that is interdependently and recursively determined by the design solutions to be evaluated (Zeng 1989; Zeng and Cheng 1991).

A great hope for resolving the contradiction in developing effective design methodologies lies in the thorough understanding of the designers' cognitive processes such that the methodologies may either lead the designers to a better approach or assist the designers in their natural manner for delivering creative solutions. This may lead to the studies in descriptive models of design processes. Finger and Dixon (1989) divided the studies in descriptive models of design processes into two categories: one that gathers data on how designers design and the other that builds models of the cognitive process. Later, Horváth (2004) and Tomiyama (2006) pointed out descriptive models of design processes is one of the core categories of design theory and methodology research. The descriptive models of design processes can be used to describe, simulate or explain the designers' mental and cognitive processes of how designers create design concepts. Some researchers have attempted to investigate designer's mental model and problem-solving behaviors using protocol studies, cognitive models and case studies. Protocol analysis has been used increasingly since the 1980's in investigating the process of designing and in understanding how designers design (Eckersley 1988; Stauffer and Ullman 1991; Lloyd et al. 1995; Purcell and Gero 1998; Atman et al. 2005; Jin and Chusilp 2006). Stempfle and Badke-Schaub (2002) studied three laboratory teams solving a complex design problem to investigate the cognitive processes of design teams during the design process. Fuchs-Frohnhofen et.al. (1996) used a methodology incorporating the taxonomy of mental models to analyze the user's mental models in work setting and generate variants of human-machine interfaces to match the user's mental models. Goldschmidt (1994) pointed out in his study that through fluid gestures and smooth hand-eye coordination, engineers not only attempt to capture their flow of thoughts, but also use their sketches to generate new ideas and images in their minds to show the importance of visual thinking for producing creative thoughts. Most of the descriptive models for studying the question how designers create designs are based on observations and implications about designer's mental model and cognitive process. It is essential to find a design model to systematically reflect the nature and characteristics of a design process and naturally accommodate designer's cognitive activities.

A new design methodology, environment based design (EBD), developed by Zeng (2004a, 2004b) can be used not only as a prescriptive methodology to guide designers to generate and evaluate design concepts, but also as a descriptive model to illustrate how designers deliver a design task. EBD includes three main stages in the process flow: environment analysis, conflict identification, and concept generation. There are four theorems implied in EBD as its theoretical foundations. Chapter 3 has given the details of the process flow and the four theorems of EBD. In this present chapter, the protocol data is used to examine the process flow of EBD and the four theorems implied in EBD. If the examination results of the protocol data match with the principles and mechanisms implied in EBD, EBD can be used as a descriptive design model to describe and explain designers' cognitive activities.

5.2 An Example of the Protocol Data

In the protocol analysis experiment, seven subjects were asked to design a new litter disposal system in a passenger compartment for railway trains and were interviewed to recall their design processes. The subjects' narrations collected from the interview session were transcribed, segmented and encoded. The protocol analysis experiment has been elaborated in Chapter 4. One of the objectives of the experiment is to evaluate environment-based design. It is impossible and not necessary to show how all design states of all the designers evolve in their design processes and how the design processes match with the EBD design model in this present thesis. Without the loss of generality, this present chapter uses the protocol data of subject 1 to evaluate the environment-based design. A part of the transcript from subject 1 is given as follows.

"......

Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table. It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats and tables (point to the sketches on the screen). This place (right under the seats) is not convenient for picking up by cleaners. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle.

......"

The segmentation of this part of the transcript is shown in Table 4-2. This part of the transcript has three design states. The segmented transcript is then encoded into different design states shown in Table 4-3. In each design state, the environment components, generated product concept and the relationships between environment and product are identified. Here, the encoded protocol data based on the design states is listed again for the succeeding evaluation of EBD.

Design state i+1: "Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table."

e_1=cleaner, e_2=table, e_3=aisle, e_4=S_{i-1}=a garbage bin

s_i=the location of the garbage bin: to put the garbage bin under the table

S_i=$S_{i-1}\cup s_i$=the location of the garbage bin is specified to be under the table

$R(e_1, e_4)$= cleaners pick up garbage from the garbage bin;

$R(e_1, e_3)$=cleaners walk along the aisle;

$R(e_2, e_4)$= garbage bin is put under the table;

Design state i+2: "It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats and tables (point to the sketches on the screen)."

e_1=passenger, e_2=seats, e_3=table, e_4=S_i=the location of the garbage bin is specified to be under the table

s_{i+1}=the location of the garbage bin: to put the garbage bin under the seats

S_{i+1}=$S_i\cup s_{i+1}$=the location of the garbage bin is specified to be under the seats

$R(e_1, e_4)$= the location of putting garbage bin under the table affects the movement of passenger's legs;

$R(e_2, e_3, e_4)$= the only place is under the seats considering seats and tables.

Design state i+3: "This place (right under the seats) is not convenient for picking up by cleaners. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle."

e_1=cleaners, e_2=seats, e_3=aisle, e_4=S_{i+1}=the location of the garbage bin is specified to be under the seats

s_{i+2}=the location of the garbage bin: to put the garbage bin along the side of the seats close to the aisle

S_{i+2}=$S_{i+1}\cup s_{i+2}$=the location of the garbage bin is specified to be along the side of the seats close to the aisle

$R(e_1, e_4)$=the location of putting garbage bin under the seats is not convenient for cleaners to pick up;

$R(e_2, e_3, e_4)$= considering putting the garbage bin along the side of seats close to the aisle

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5.3 Results and Discussions

5.3.1 Process flow

As introduced in Chapter 3, the process flow of environment-based design has three main stages: environment analysis, conflict identification, and concept generation. The process flow of EBD can be taken as the general process that designers follow to solve design problems. Designer may not be aware of the process, but this process flow is implied in designers' design processes and can be used to explain designers' cognitive activities.

For the example of the protocol data of subject 1, in design state i+1, the subject identified four environment components: cleaner, table, aisle, and the garbage bin; then he tried to analyze the relationships between these environment components; he figured out that the cleaner must walk along the aisle and need to pick up garbage from the garbage bin and there is conflict among cleaner, aisle, table and garbage bin; to solve this conflict, he figured out the concept to put the garbage bin under the table. He took this concept to go into the next design state. In design state i+2, the subject introduced extra environment components: passengers, seats and the concept generated in design state i+1; with more environment components, he identified another conflict that the garbage bin under the table affects the movement of passenger's legs; to solve this conflict, he proposed another concept to put the garbage bin under the seats. In design state i+3, the subject considered the environment components: cleaner, seat, aisle and the concept generated in design state i+2 and their relationships; then identified another conflict that putting garbage bin under the seats is not convenient for cleaners to pick up garbage; so, he modified the concept in design state i+2 by considering to put the garbage bin along the side of seats close to the aisle. The process flow of the three design states is summarized in Table 5-1.

Table 5-1 The process flow of the protocol data

	Environment analysis	Conflict identification	Concept generation
Design state i+1	Cleaner, table, aisle, and the garbage bin	The cleaner must walk along the aisle & need to collect garbage from the garbage bin	To put the garbage bin under the table
Design state i+2	Passenger, seats, table, and the location of the garbage bin specified to be under the table	The garbage bin put under the table can affect the movement of passenger's legs	To put the garbage bin under the seats
Design state i+3	cleaners, seats, aisle, and the location of the garbage bin specified to be under the seats	Putting garbage bin under the seats is not convenient for cleaners to pick up garbage	To put the garbage bin along the side of seats close to the aisle

This design process continues until the subject thinks no more unacceptable environment conflicts exist. Although this section only explained the evolution of the three design states of subject1's design process, the other design states evolve in the same way following the process flow of EBD.

5.3.2 Recursive logic of design

As explained in the theorem of recursive logic of design, a design solution must pass an evaluation defined by the design knowledge that is recursively dependent on the design solution that is to be evaluated. In a design process, designers first identify the possible environment components around the product and then think about their interactions between environments components and the product. From the interactions, product requirements are generated. The product requirements may lead to some design solutions. The design solutions are evaluated by designers' knowledge while the design knowledge comes from designers' understanding of the product requirements. So, it can be seen, in a design process, product requirements and design solutions change together. Design solutions are usually represented by descriptions of the product property. To reflect the changes of the product requirements and design solutions, design state can be used to represent the changes at each stage of the design process. A design state is composed of the product requirements and the product descriptions at a specified stage of the design process.

For the example of the experiment, in the design state i+1, the designer first identified four environment components: cleaners, table, aisle and the previous design solution to design a garbage bin; and then he considered the interactions of these environment components; he thought about the interaction between cleaners and garbage bin: "cleaners pick up garbage bin", the interaction between cleaners and the aisle: "cleaners walk along the aisle", and the interaction between garbage bin and the table: "garbage bin is put under the table". The product requirements are formed based on these interactions. If there is any concept generated in this design state, it must be evaluated by the designer to generate next concept. However, the environments identified in this design state and their interactions may not lead to the same concept, "to put the garbage bin under the table"; different designers may generate a different concept based on their knowledge to analyze the environments. The knowledge that the designer used to evaluate a concept to be generated can be defined only when the concept is generated. The knowledge is defined when the designer thought how the concept of putting the garbage bin under the table will interact with the cleaners, the table, the aisle and their interactions. In this design state, the knowledge defined to evaluate the concept is that the cleaners walk along the aisle and they can pick up the garbage bin conveniently if the garbage bin is put under the table.

Similarly, in the design state i+2 and the design state i+3, the concepts generated are evaluated by the knowledge which are defined from the concept. With the evolution of the design states, a design problem can be solved. So a design process can be represented by a series of design states. In each design state, the product requirements are identified by considering the interactions between environment and product. Then, a concept is generated based on the product requirements. The concept is represented as the descriptions of the product properties.

5.3.3 Source of product requirements

The theorem of source of product requirements states that all the product requirements in a design problem are imposed by the product environment in which the product is expected to work (Zeng 2004a; Chen and Zeng 2006). A design process is composed of a series of design states and a design state is characterized as the product requirements and the product description at a specified stage of the design process. The product requirements are formed based on the interactions of the identified environments. From the product requirements, design solutions can be generated through designer's design knowledge. So it can be seen that the driving force of a design process comes from environment and the source of product requirements comes from the identified environment components.

For the example of the protocol data, in the design state i+1, the environments (E_i) in this design state are cleaners (e_1), table (e_2), aisle (e_3) and garbage bin (e_4). Then the designer thought about the relations (B_i) between these environment components. So he got the product requirements for the concept of specifying the location of the garbage bin. The product requirements are: 1) the cleaners can pick up garbage bin if the garbage bin is put somewhere; 2) the cleaners walk along the aisle to pick up garbage bin; and 3) garbage bin can be put under the table in the train. It can be seen that the identified environment components and their relationships decide the product requirements.

In the design state i+2, the previous design solution, (to put the garbage in under the table) is included in the current environment system and the current design solution is taken as a part of the environment components in the next design state i+3. The interactions between environment and product in the design state are the result of considering the interactions among different environment components. And the product requirements can be defined by environment components in which the product is expected to work. So it can be seen that a design state can be represented by the environment structure. A design process consists of many design states and each design state is composed of environment components and their interactions. So the driving force of the design process comes from environment and the design state changes according to the changes of the environment.

5.3.4 Dynamic structure of design problem

As stated in the theorem of dynamic structure of design problem, design solutions to a design problem may change the original design problem in the design process if the design solutions are different from their precedents, either by refinement or by alteration. In a design state, the concept generated in the previous design state is evaluated by considering other environment components; new design requirements may be generated; this is an evaluation process. Then based on the design requirements, a new concept can be generated by designers; this is a synthesis process. The synthesis process is responsible for proposing a set of candidate product descriptions based on design requirements. The evaluation process is used to screen candidate products against design requirements. So, the design solutions in one design state could be modified or changed from the previous design state through the interactions of synthesis and evaluation. The interaction of synthesis and evaluation gives rise to the final balanced design solutions.

In the design state i+1, the designer considered the interactions of cleaners, table, aisle and the previous design solution to design a garbage bin. The environments are cleaners, table, aisle, and garbage bin. The generated concept is the location of the garbage bin specified to be under the table. In the design state i+2, the design solution generated in design state i+1 is taken as an environment component and considered other environment components: passengers, seats and table; so, the environment is composed of passengers, seats, table and the concept generated in design state i+1. Then, the designer evaluated the previous concept by considering all these environment components and the interactions between these environment components. He thought this design solution is not convenient for passengers to move their legs; thus, the previous design solution is rejected. So, this evaluation can be represented by the evaluation operator of K^e_{i+1}. Then, the designer considered the identified environment components and their interactions and tried to generate a new concept. The newly generated concept, S_{i+1} is to put the garbage bin under the seats. The generation of the new concept can be represented by the synthesis operator of K^s_{i+1}. The transition from the design state i+1 to the design state i+2 is $\oplus E_{i+2} = K^s_{i+1}(K^e_{i+1}(\oplus E_{i+1}))$. So, it can be seen the change or modification from one design state to the other state is the result of evaluation and synthesis.

In the design state i+3, the designer considered the concept in design state i+2 as an environment component. Then, the environment components are cleaners, seats, aisle and the concept generated in design state i+2. The designer evaluated the design solution in design state i+2 and he thought putting the garbage bin right under the seats is not convenient for cleaners to collect garbage. This evaluation can be represented as K^e_{i+2}. Then, he modified the previous design solution and the design solution in this design state is to put the garbage bin along the side of the seats close to the aisle. The modification of the previous concept can be represented as K^s_{i+2}. So the transition from the design state i+3 to the design state i+2 is represented in $\oplus E_{i+3} = K^s_{i+2}(K^e_{i+2}(\oplus E_{i+2}))$.

Therefore, the three design states showed that in the design process, design solutions to a design problem may change the original design problem, if the design solutions are different from their precedents, either by refinement or by alteration.

5.3.5 Design driving force

The theorem of design driving force states that the driving force behind the design process is the undesired combined conflicts existing in an environment system. A design process continues until no such conflicts exist. It is necessary to first identify the conflicts existed in the design states.

In the example of the protocol data, the design state i+1 has the conflict between the garbage bin and the cleaners. The cleaners want to pick up the garbage bin conveniently while the location of the garbage bin is constrained in the compartment. So, the designer thought about the cleaners, the table, the aisle and the garbage bin in the train and generated the solution to put the garbage bin under the table.

However, in the next design state i+2, the concept of putting the garbage bin under the table has conflicted with the environment component of passengers since that location of putting the garbage bin under the table will affect the movement of the passenger's legs. So, this conflict has to be resolved. Then, the designer thought to put the garbage bin under the seats to solve the problem.

Then, in design sate i+3, the designer tried to evaluate the previous concept by considering whether this concept is convenient for cleaners and found that the previous concept of putting garbage in under the seats conflicts with the cleaners. The conflict is resolved by modifying the previous concept as putting the garbage bin along the side of the seats close to the aisle.

These are just three design states in the design process. The conflicts in the succeeding design states are identified and resolved until no critical conflict can be found in the design states. When no conflicts can be identified, the design problem is solved. The design concept in the last design state is the final design solution. In this example, the final design state is described as follows.

"The (garbage) bag stops, it can be open with a zipper for the passenger to deposit garbage. When it is moving, it is closed. So the garbage bag stops and moves for several blocks until it is filled. Then we will collect the whole garbage bag from the other end of the compartment. Then we will change a new bag in the garbage channel."

The environments in this design state are passenger, garbage, compartment, cleaners, garbage channel, garbage bag and the concept in the previous design state. The previous concept is shown in the following graph.

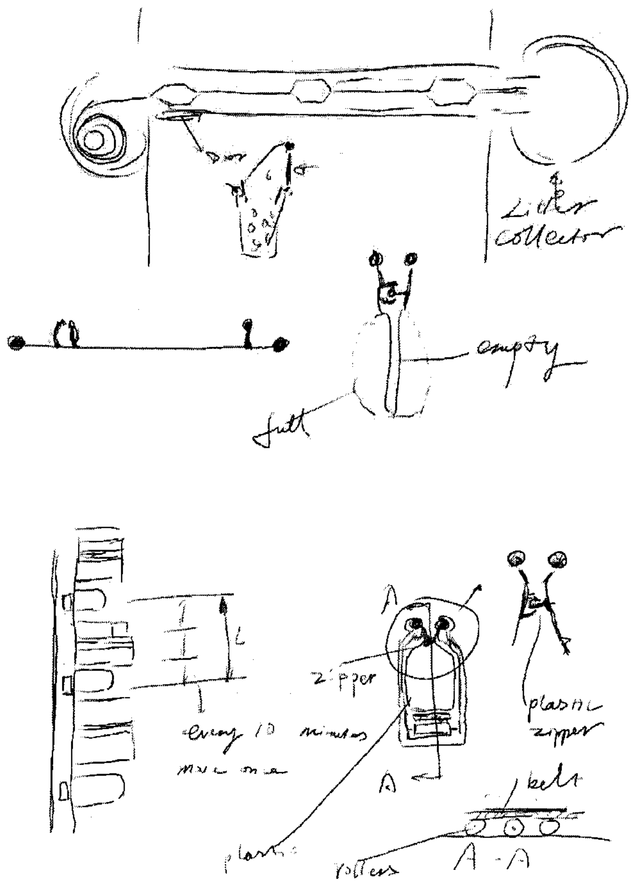


Figure 5-1. Sketch of final design solution.

The system that the designer designed for passengers to deposit garbage is a conveyor belt system. This system is installed inside the wall of the compartment; there is a garbage channel in the system; a garbage bag can be rolled and installed from one side of the compartment and collected at the other side of the compartment; the movement of the garbage bag can be controlled.

The designer, in the final design state, evaluated the previous design solution with other environment components and found there is no conflict from the interactions between environment and product. So, the design process stops since no conflict can be found and the design solution in this design state is the final design solution.

5.4 Concluding Remarks

This chapter has used a part of the protocol data of subject 1 to evaluate and examine the environment-based design as a descriptive model of design processes (Yao and Zeng 2007c). The results have shown the design process of subjects 1 matches with the process flow and the four theorems of EBD. EBD is a prescriptive design methodology, which can guide designers from the gathering of customer requirements throughout the generation and evaluation of design concepts. Subject 1 didn't use EBD as a design methodology to solve the design problem, but his design process can reflect the process flow of EBD and the four theorems implied in EBD. So, it can be seen that EBD is also a descriptive model of the natural design process to illustrate how designers conduct a design task.

Chapter 6
Virtual Experiment

In this chapter, a virtual experiment is developed for understanding design activities and for validating design theories. Three hypotheses are proposed by summarizing the typical design activities and phenomena. They are: 1) formulating the design problem differently at the beginning of a design process may get quite different solutions, in which creative design could emerge; 2) changing the sequence of design problem decomposition may change product requirements, and thus change the generated design concepts; 3) extending designers' knowledge and experience can help generate more candidate solutions concepts, and so increasing the probability of generating a good concept. The environment-based design theory (EBD) is used to provide logical interpretation to the hypotheses and is used as the foundation for the simulation of the design process. A virtual experiment based on the EBD theory is designed and conducted to test the aforementioned three hypotheses.

This chapter is organized as follows. Section 6.1 gives an introduction of the virtual experiment. Hypotheses of conducting the virtual experiment are proposed in Section 6.2. The design of the virtual experiment is elaborated in Section 6.3. The results and analysis are given in Section 6.4. Section 6.5 concludes this chapter.

6.1 Introduction

A good design theory should be able to explain the phenomena in design activities and in return, the phenomena should be able to support and enrich the theory. Thus, it would be beneficial to find an effective experimental method to verify a design theory, to simulate designer's activities and to fill the gap between the real design activities and design theories. Inspired by the success of simulation and virtual experiment in many other fields such as construction (Li et al. 2003), hydrology (Weiler and McDonnell 2004; Weiler and McDonnell 2006), education (Marinov and Andonov 1997), computer science (Dam et al. 2002), and human experience (Takatalo et al. 2008), this present research uses virtual experiment to simulate design activities and validate the general observations about the design activities.

The foundation of the virtual experiment is the Environment Based Design (EBD) theory. Figure 6-1 illustrates the structure of the present research. The EBD theory has been introduced to interpret theoretically observations and assumptions about design activities in Chapter 3. It is also used to aid the design of the virtual experiment as a simulation model of the design process. The data collected from the virtual experiment is used to validate the hypotheses derived from properties of design activities.

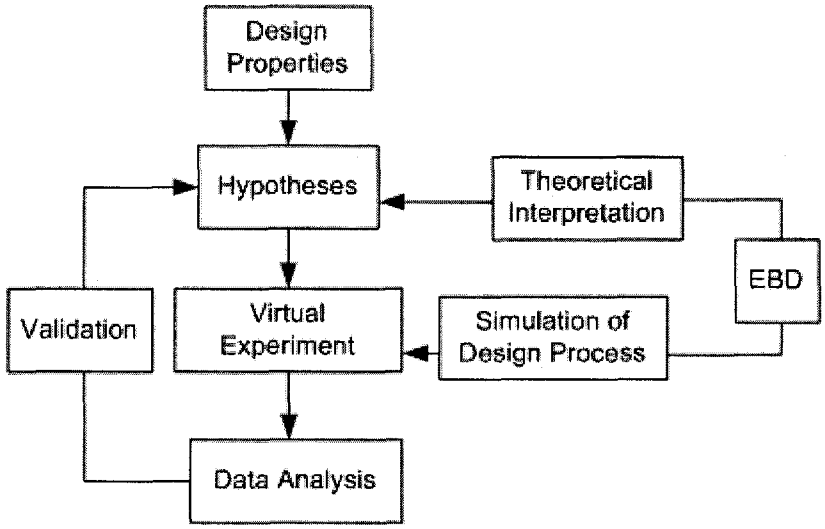


Figure 6-1 Structure of virtual experiment on design activities.

6.2 Hypotheses

The virtual experiment is developed to test the following hypotheses.

1) *Formulating the design problem differently changes design solutions.* It can be expected that formulating the design problem differently will get different requirements for a design problem. With different requirements, the solutions will be generated differently.

2) *Changing the sequence of environment decomposition leads to different design solutions.* A design problem can be decomposed into various sub-problems. It can be expected, with different sequence of environment decomposition, the design solutions will be different.

3) *Extending* synthesis *knowledge leads to different design solutions.* For specified requirements, the more synthesis knowledge a designer has, the

more concepts could be generated, which could lead to a better design solution.

6.3 Design of Virtual Experiment on Design Activities

As was shown in Figure 6-1, the objectives of the virtual experiment are to simulate different design properties that can explain the mechanism of design activities and phenomena. Based on EBD and observations of design properties, there are three routes leading to different design solutions: formulating the design problem differently, extending synthesis knowledge and changing the sequence of environment decomposition. In the virtual experiment, these three routes are quantified to show the effects of the differences on design solutions.

6.3.1 Statement of the problem

Virtual experiment allows a user to interact with a computer-simulated environment to simulate different real situations. It is not only cost-effective, but also can be easily and quickly operated to present the real problem in many different perspectives in a virtual environment. There are few publications in design research addressing virtual experiment to understand a design process. However, it has been widely used in various research areas (Marinov and Andonov 1997; Li et al. 2003; Weiler and McDonnell 2004; Keim et al. 2006; Weiler and McDonnell 2006). In this present research, the virtual experiment environment is presented to simulate the design process for solving a design problem and validate the observations generated from environment-based design.

To investigate the mechanism of the design process, the virtual experiment should be isomorphic to real design activities. The first challenge in designing the virtual experiment is to select a suitable design problem to be simulated. The design problem to be selected should be easily understandable and not need much domain knowledge. Moreover, the design problem should be inclusive so that most of design phenomena can be displayed. Then the design process of solving such a design problem can be simulated by a computerized model. This computerized model has various options to change parameters and strategies to solve the design problem, and then, different settings can be combined to generate different solutions. In addition, it is necessary to establish evaluation criteria to evaluate different design solutions and compare them.

6.3.2 Design problem

As mentioned earlier, the design problem used in a virtual experiment should be easily understood, domain independent, and inclusive, so that typical phenomena of underlying general design process can be displayed. The selected design problem must satisfy the following requirements: 1) it is isomorphic to any other design problems, such as mechanical design, architectural design, or electrical design etc.; 2) the problem can be easily formulated; 3) its solution strategy is comprehensive, inclusive and not domain dependent. In this research, three design problems: rivet setting tool design, litter-disposal system for a railway train and automatic finite element mesh design are described and compared. The finite element mesh design problem is found to satisfy the requirements for conducting a virtual experiment.

(i) Rivet setting tool design

The rivet setting tool design example is adapted from the book by Hubka et al (Hubka et al. 1988). The task of this problem is to design a tool for riveting brake linings onto brake shoes for internal drum brakes as shown in Figure 6-2. The user of this tool is a car mechanic. The hand force, foot force, and working height should follow ergonomic standards. The use of this tool should conform to the related industry safety standards. The service life of this tool should be around 5 years. The tool should be easy for transportation and maintenance. It will be manufactured in a specific workshop, which has specified equipments. The cost of this tool cannot be over $190.00.

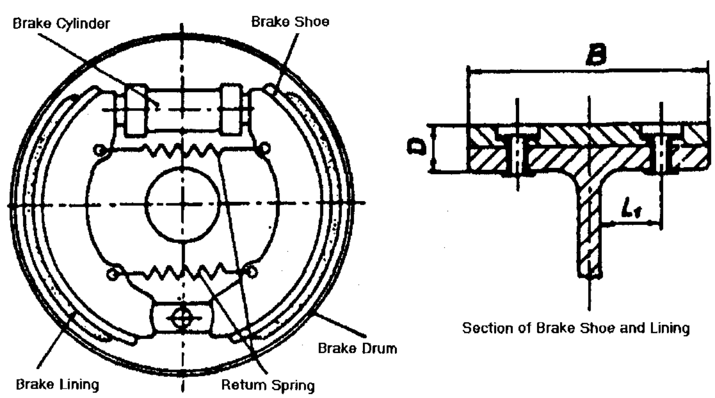


Figure 6-2 Internal drum brake (Hubka et al. 1988).

(ii) Litter-disposal system design for a railway train

The litter-disposal system is originally adapted from the research conducted by Dorst and Cross (2001). This design problem is also used in a cognitive experiment to study designer's cognitive activities (Yao and Zeng 2007a). The design problem is modified as:

to design a litter-disposal system for the passenger compartment in a railway train; this system should be convenient for the passengers to deposit garbage and meanwhile it is easy for the cleaners to collect the garbage; the structure of the passenger compartment is shown in Figure 6-3.

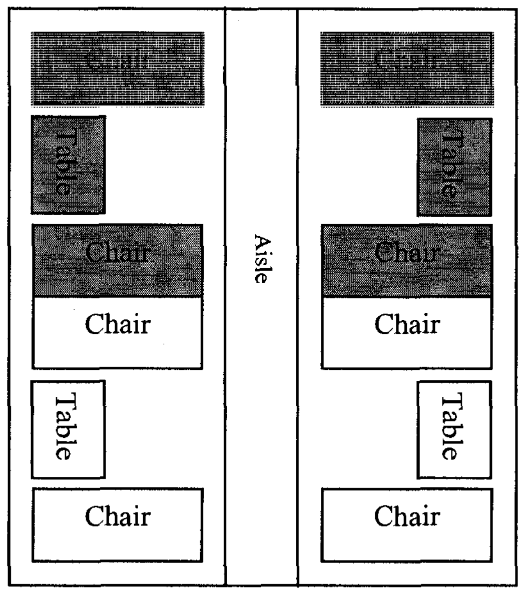


Figure 6-3 The structure of a compartment

(iii) Finite element mesh design

This problem aims to generate a quadrilateral mesh for a single-connected plane domain with even number of boundary segments. This mesh needs to satisfy the following requirements: 1) each element is a quadrilateral; 2) the inner corner of each element should be between 45° and 145°; 3) the aspect ratio (the ratio of opposite edges) and taper ratio (the ratio of neighboring edges) of each quadrilateral should be within a predefined range; 4) the transition from the dense mesh to the coarse mesh should be smooth; 5) the structural analysis error resulted from the mesh should be minimized. An example of mesh is generated as shown in Figure 6-4.

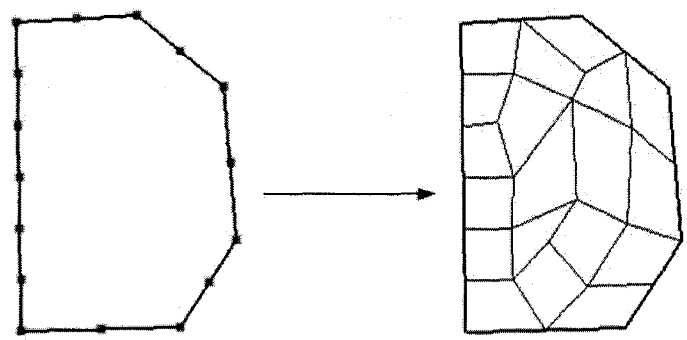


Figure 6-4 A mesh example

From environment-based design theory (Zeng 2004a), a design problem is implied in a product system and composed of three parts: the environment in which the designed product is expected to work, the requirements on product structure, and the requirements on performances of the designed product. Based on the structure of the design problem, the product to be designed, product environments, performance requirements and structural requirements for the above mentioned three problems are summarized in Table 6-1.

Table 6-1 The structure of three problems

	Rivet setting tool design	Litter-disposal system design	Mesh generation design
Product	tool	Litter-disposal system	Mesh
Product environment	• Nature • Mechanics • Manufacturing Shop • Transportation facilities • Market • Brake: linings and shoe.	• Train • Compartment • cleaner/garbage collector • railways/user • manufacturer • passenger • garbage	A single-connected plane domain with even number of discretized boundary segments.
Performance requirements	R-R1. To rivet brake linings onto brake shoes. R-R2. The hand and foot forces should follow ergonomic standards. R-R3. The use of the tool should conform to related industry safety standards. R-R4. The tool can be manufactured in the specific workshop. R-R5. The service life of the tool will be around 5 years. R-R6. The tool should be easy for transportation and maintenance. R-R7. The cost of the tool cannot be over $190.00	R-L1: The system should be convenient for the passengers to deposit garbage; R-L2: The system should be easy for the cleaners to collect the garbage; R-L3: The system is used in the train and should keep static when the train is moving; R-L4: The system should be acceptable for the railway company; R-L5: The system should be produced to fit the requirements of the manufacturer	R-M1: The structural analysis error resulted from the mesh should be minimized.
Structural requirements	R-R8. The working height should follow ergonomic standards	R-L6: The system should fit the structure of the compartment; R-L7: The system can contain different garbage deposited by the passenger.	R-M2: Each inner corner of a quadrilateral should be within a predefined range. R-M3: The aspect ratio and taper ratio of each quadrilateral should be within a predefined range. R-M4. The transition from the coarse mesh to the dense mesh should be smooth

It can be seen that all the three problems can be represented by the structure of a design problem. From the three design problems, product, environment and the product requirements have been identified. Both the rivet setting tool design and litter-disposal system require designers to have some domain knowledge to solve them. The processes of solving the two design problems are not easily formulated since they involve a lot of drawings and representations. However, the mesh generation design problem is isomorphic to the other design problems; it can be easily formulated and represented; the mesh element can be generated without any domain knowledge. Therefore, the automatic finite element mesh design is selected as a design problem used in the virtual experiment.

Figure 6-5 shows the process of a mesh generation example. In this mesh generation problem, the product is a quadrilateral mesh. The environment is the domain boundary. So the state of the mesh generation problem can be represented as

$$\oplus E_{i+1} = \oplus(E_i \cup S_i) = \oplus E_i \cup \oplus S_i \cup (E_i \otimes S_i) \cup (S_i \otimes E_i)$$

where E_i is the domain boundary and S_i is the generated finite element mesh.

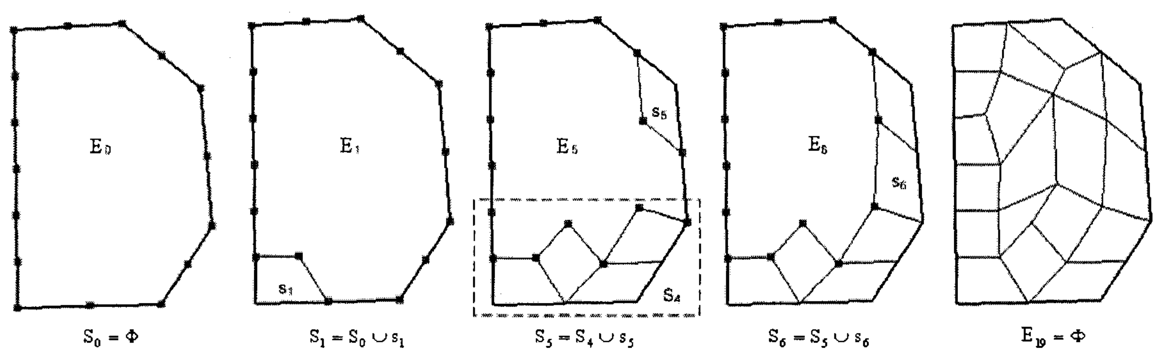


Figure 6-5 Quadrilateral mesh generation by element extraction (Yao et al. 2005).

It can be seen that in each step, the generated finite element mesh S_{i+1} is the combination of the previous mesh S_i and the newly generated element s_{i+1}; the updated boundary E_{i+1} is the result from removing the newly generated element s_{i+1} from the previous boundary E_i. This process will continue until the domain is filled with required elements.

In the mesh generation design problem, first environment analysis is first conducted to figure out the environment is the domain boundary and the product is the elements to be generated around the boundary. Then, for some complex boundaries, the if-then rules could generate an element which does not satisfy the design requirements; this element could affect the succeeding generated elements by updating the boundary, so the conflicts between the quality of the element and the if-then rules are then identified. It is necessary to check the design requirements again and adjust the if-then rules. So, the final generated mesh is the result of the interaction between evaluating the generated element quality and synthesizing the if-then rules. Therefore, the process of the mesh generation reflects the characteristics of a design process.

6.3.3 Evaluation criteria

It is a mathematically challenging problem to calculate the structural differences of two meshes. To compare the differences of two meshes, the present research considers how the meshes satisfy the problem requirements. In terms of the requirements for the mesh, the best quadrilateral is square and the transition from the coarse mesh to the dense mesh should be smooth. Based on the requirements of mesh quality, the criteria for evaluating element quality and transition quality are developed as below.

Element quality criteria

In a single connected domain, there are n quadrilateral elements. For each quadrilateral element i, the present study compares the area of the quadrilateral (s_i) with the area of the corresponding square (s_{i0}), which has the same circumference as that of the quadrilateral. The ratio, R^e_i between the area of the quadrilateral and the corresponding square area is $R^e_i = \frac{s_i}{s_{i0}}$. Since the area of a quadrilateral is not bigger than the corresponding square area having the same circumference as that of the quadrilateral, it can be concluded the area ratio, R^e_i is not bigger than 1, namely, $R^e_i \le 1$. Each element with good quality should be close to its corresponding square and its ratio should be close to 1.

For n elements, the mean value of all element area ratios is $\overline{R}^e = \frac{\sum R^e_i}{n}$. An upper limit and a lower limit around the mean value are set to see how many element area ratios are within the lower and upper limit, as shown in Figure 6-6 . The lower limit can be taken as 30% off down from the mean value of all element area ratios in a domain. Since the area ratio is not bigger than 1, the upper limit can be taken as 1. The percentage of the number of the element area ratios outside of the lower and upper limit can be used to evaluate the element quality for the whole domain. The element quality criteria for the whole domain is given as $R^e = \frac{\text{NO. of element outliers}}{n}$. A big value of R^e means more poor quality elements and indicates a big difference of quality among all elements of the mesh. A smaller value of R^e means fewer elements are out of the boundary of element quality.

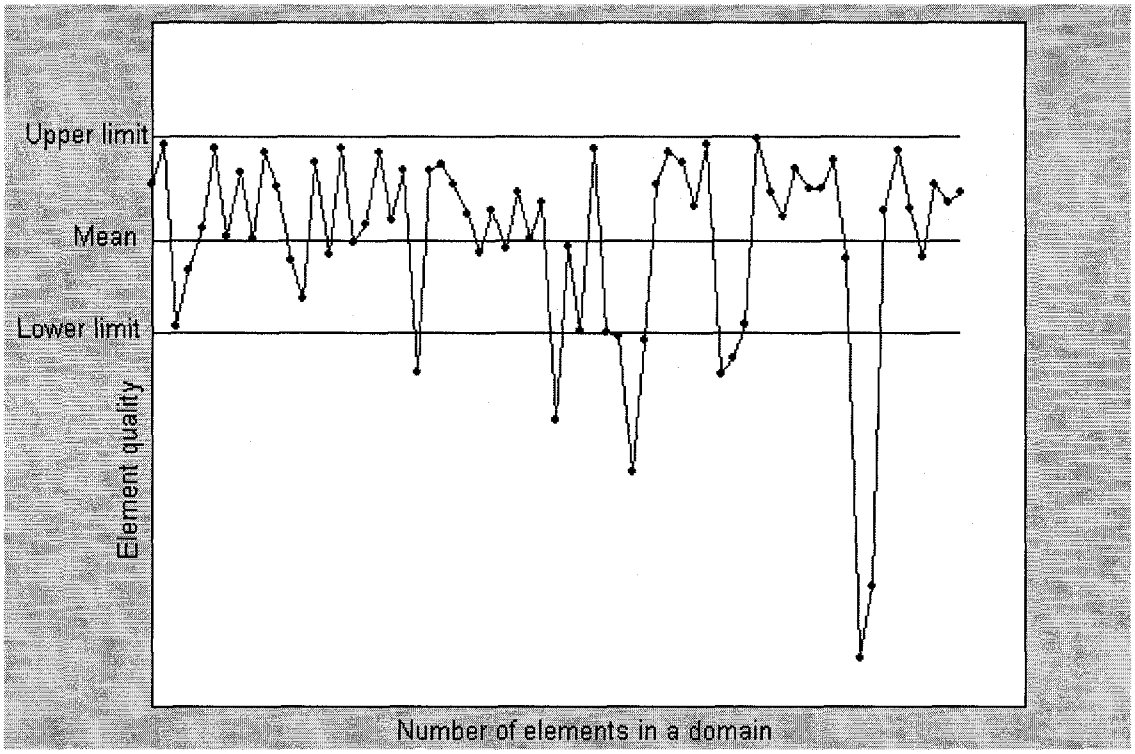


Figure 6-6 Outliers for element quality.

Transition quality criteria

In a domain, s_i and s_j represent the areas of an element i and its neighboring element j respectively. The areas of the neighboring elements are compared to evaluate the transition from coarse mesh to dense mesh. Then, the transition ratio between two neighboring elements is generated as,

$$R_{ij}^{t} = \left(\frac{S_i}{S_j}\right)^k, \quad k = \begin{cases} \dfrac{S_j - S_i}{|S_i - S_j|} & S_i \neq S_j \\ 0 & S_i = S_j \end{cases}$$

The transition ratio can be used to evaluate how close the two neighboring elements are. It is assumed that there are m different pairs of neighboring elements in a generated mesh domain. Those neighboring elements must not be repeated to avoid the recalculation. Then, the mean of the transition ratios in the domain is $R^t = \frac{1}{m}\sum R_{ij}^t$. Then, the upper and lower limits are set around the mean of the transition ratios. From the definition of the transition ratio, it can be found that $R_{ij}^t \le 1$ since it is the ratio between the small area and the big area. So the upper limit is set as 1. The lower limit is given as 30% off down to the mean of the transition ratios. The transition quality criteria for the whole domain can be defined as the percentage of the number of transition ratios outside the lower and upper limit in the number of the pairs of neighboring elements, namely, $R^t = \frac{\text{NO. of transition outliers}}{m}$, as shown in Figure 6-7.

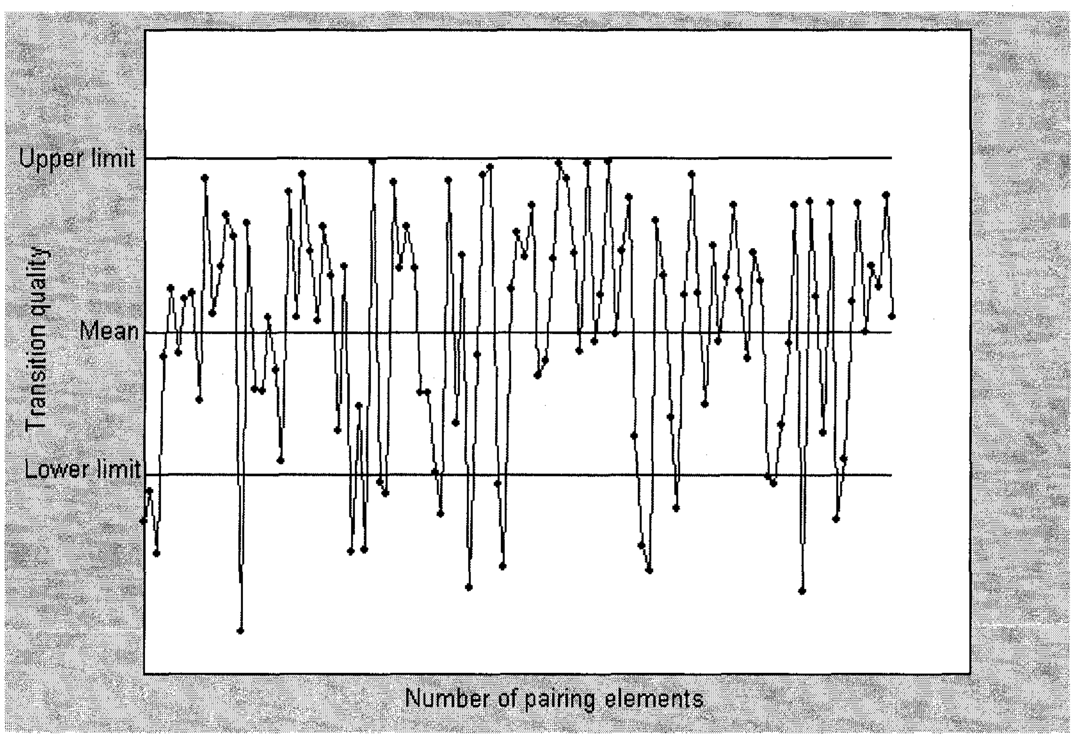


Figure 6-7 Outliers for transition quality.

Therefore, the criteria of a mesh quality can be defined as the sum of the element quality criteria and the transition quality criteria, as $R = R^e + R^t$. A small value of R shows good mesh quality for a domain.

6.3.4 Virtual experiment environment

An automatic mesh generation program has been developed under the development environment of Visual C++. Net 2003 (Zeng and Cheng 1993; Yao et al. 2005). This program can automatically generate a mesh in a pre-defined domain based on element extraction method. The interface of this experiment with a sample result is shown in Figure 6-8. With this interface, different solutions can be generated by 1) simulating to formulate the design problem differently, 2) simulating to apply different synthesis knowledge, and 3) simulating different environment decomposition sequences.

The following is a brief introduction to the functionality of the interface.

- Create a boundary (define the original problem). Moving and clicking the mouse can draw the boundary polygon.
- Edit the boundary (redefine the problem). You can add a new point on the boundary; change the coordinate of a point; change the base length or density of a point; or change the range of the inner corner of an element.
- Generate a mesh by specifying the number of elements generated each time.
- Select different decomposition strategies. Three modes are provided to simulate the decomposition strategy. You can solve the problem automatically by selecting one decomposition strategy.

- Select different sets of synthesis operators to simulate different designers. There are five heuristic rules to generate an element. An artificial neural network-based element extraction method is also developed, which will be elaborated in Chapter 7. The mesh can be also manually generated by simply connecting the related points.
- Simulate to create different primitive environment.
- Examine the sensitivity of design solution to a small change by user intervention during automatic design.
- The generated mesh can be cleared and regenerated in the same domain. A generated element can be also cleared and regenerated manually.

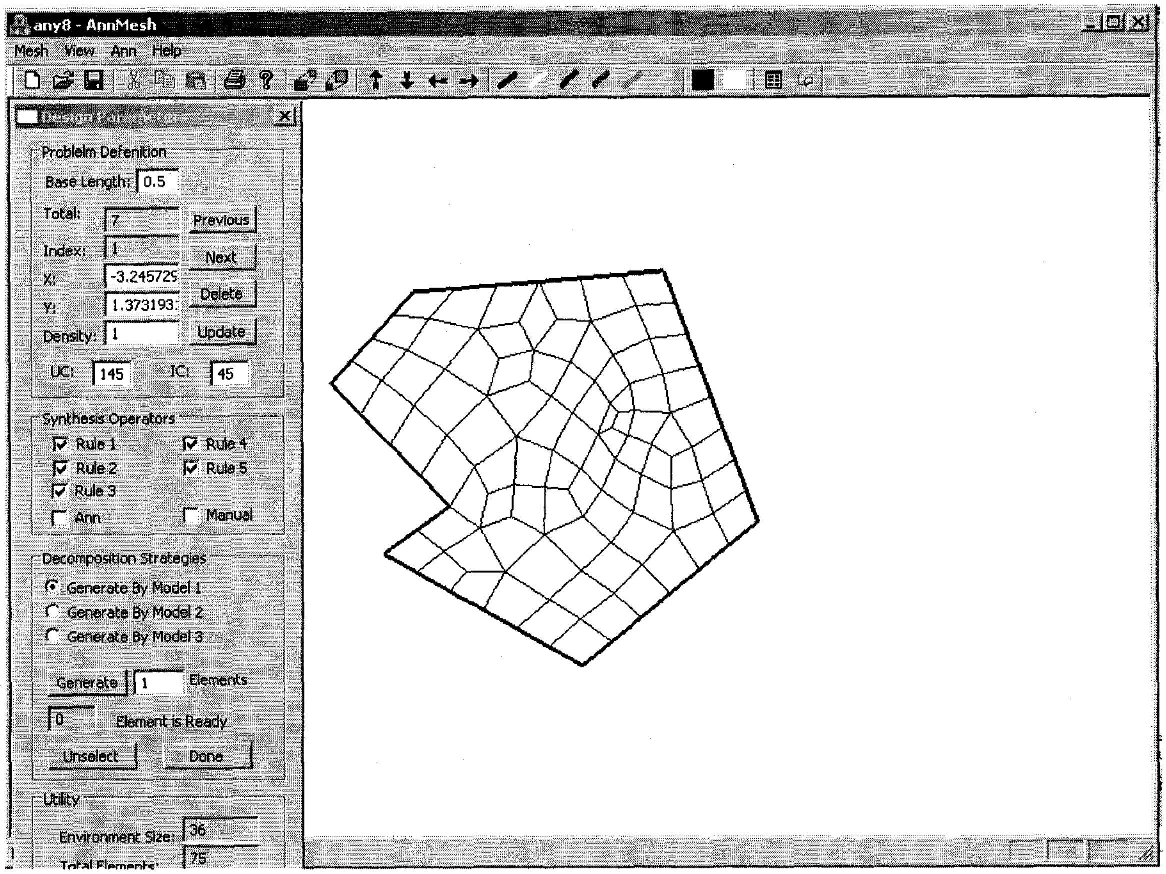


Figure 6-8 The interface of the mesh generation system.

6.4 Results and Analysis

For the design problem of mesh generation, the product requirements are the requirements for the generated mesh quality and the product is the generated mesh element. The mesh elements are generated one by one. Each element is generated based on the interaction between the previous generated elements and the environment. Then, the newly generated element is evaluated for the generation of the next element. This evolution process continues until the domain is filled with all elements. Figure 6-9 is an example of the process of mesh generation.

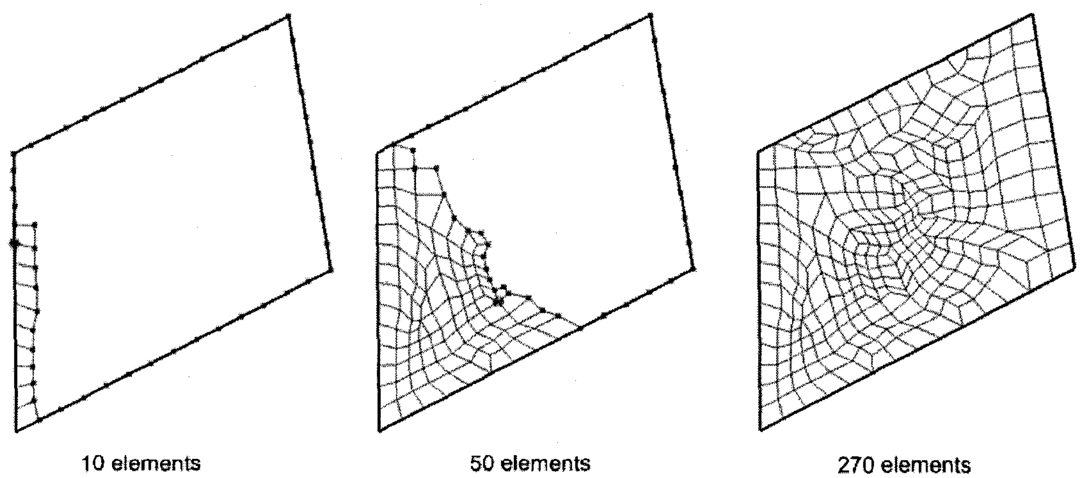


Figure 6-9 An example of the process of mesh generation.

Figure 6-10 shows the changes of the mesh quality with the increasing of the number of generated elements. At the beginning of the mesh generation, the generated elements have relatively good quality since the boundary feature is not complex. When more elements are generated, the boundary feature becomes more complex and the previously generated elements also affect the quality of the succeeding mesh elements. Thus, the mesh quality becomes worse when more elements are generated. This process of the mesh generation corresponds to the general design process. In a design process, a design concept at the beginning can be generated very well based on one product requirement. When considering more other product requirements, the design concept has to be changed, merged or modified to accommodate other design concepts. The final design solution is the interaction of evaluation and synthesis of the design concepts.

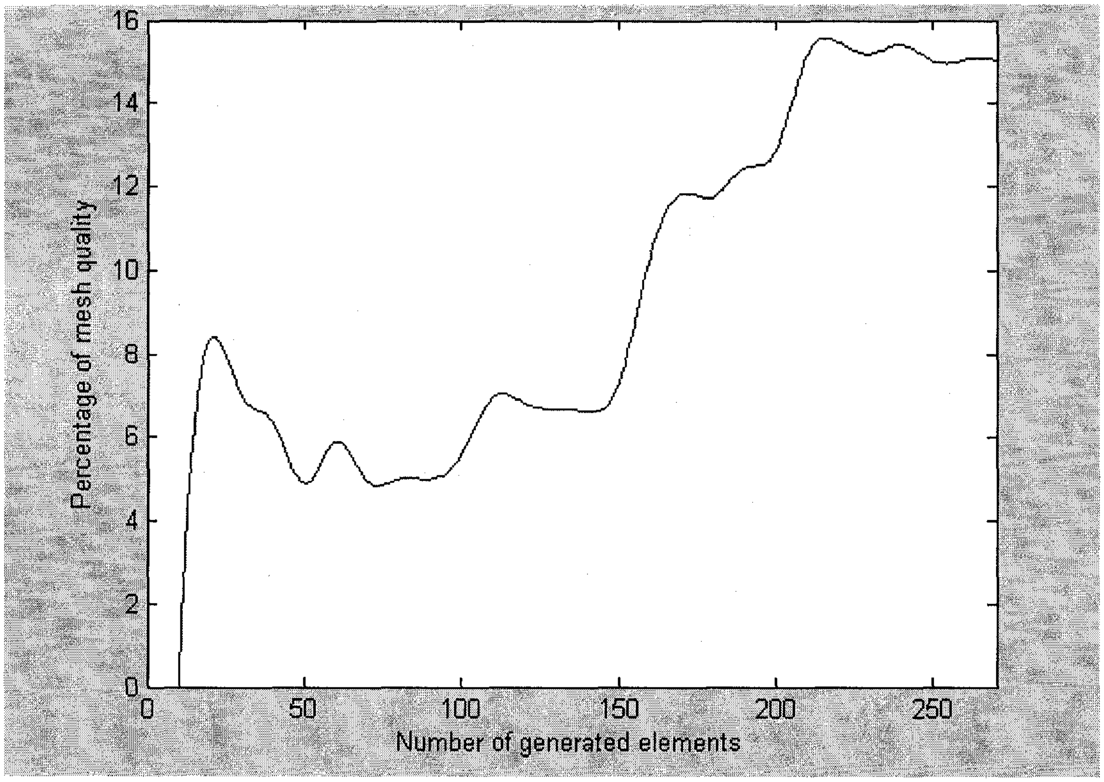


Figure 6-10 The changes of mesh quality during mesh generation.

Since design is a nonlinear process, creative design solution could be affected by many factors. As observed in Chapter 2, there are three routes leading to creative design solutions. In this present chapter, the developed mesh generation program is used to examine how the three routes: formulating the design problem differently, changing the sequence of decomposing the design problem and extending synthesis knowledge could affect the final mesh.

6.4.1 Formulation of design problem

In the design problem of mesh generation, first a single connected plane domain is given; then, the domain is decomposed to generate mesh elements. A plane domain is characterized by its vertex points and boundary segments. So, the formulation of the mesh generation problem depends on the based length to define the boundary segments, the density of the segments around each vertex and the vertex where to start the generation of mesh elements. In the program of mesh generation system, the default values for base length, density and starting vertex are 0.5, 1, and vertex 1 respectively. If the base length is smaller, there are more points on the initial boundary and the boundary segments are smaller. If the density is bigger than 1 at a specified vertex, there are more boundary points around the vertex and accordingly the mesh elements around the vertex are denser. The first element is generated around the starting vertex. Any changes of the base length, the density at each vertex, and the starting vertex could affect the final generated mesh.

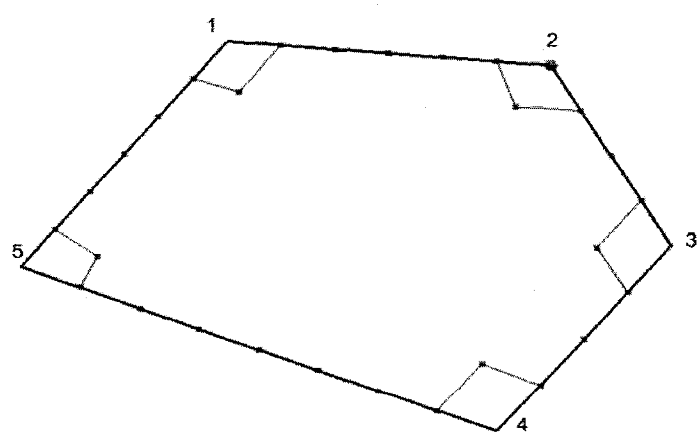


Figure 6-11 An example of the boundary.

To study different formulation of the mesh generation design problem, the base length, the density at each vertex and the starting vertex are taken as three independent variables to study the effect on the final generated mesh. It is assumed that the three variables have no interaction. The final mesh quality is the dependent variable on the three independent variables. Four levels of changes of the three independent variables are considered. The base length changes between 0.3, 0.4, 0.5 and 0.6; the density changes from 0.8, 1, 1.2 and 1.4; and the starting vertex changes from the first index to the fourth index. The index number is the sequence of the vertices when forming the initial boundary. In this research, 10 randomly generated quadrilateral domains are used for mesh generation. For each quadrilateral domain, there are 64 samples to formulate different initial conditions by combining the four levels of the three variables (4^3). Then, these samples with different initial conditions are used to generate mesh and the generated mesh is evaluated using the criteria introduced in Section 6.3.3.

The three-way analysis of variance (ANOVA) was performed with the base length (four levels), density at vertex 1 (four levels) and starting vertex (four levels) as the independent variables and the mesh quality as the dependent variable on one of the domains. The level of significance is chosen at 0.05 as a matter of convention. As shown in Table 6-2, the ANOVA results show the base length ($F=2.82 > p=0.0581$), density ($F=8.92 > p=0.0003$), and the starting vertex ($F=2.89 > p=0.0538$) have significant effects on the quality of the generated mesh. The interactions of the three effects are also significant.

Table 6-2 Three way ANOVA table

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Base length	0.00423	3	0.00141	2.82	0.0581
Density	0.0134	3	0.00447	8.92	0.0003
Starting point	0.00434	3	0.00145	2.89	0.0538
Base length*Density	0.01316	9	0.00146	2.92	0.015
Base length*Starting point	0.00485	9	0.00054	1.08	0.4114
Density*Starting point	0.0081	9	0.0009	1.8	0.115
Error	0.01352	27	0.0005		
Total	0.0616	63			

The mesh quality value of the sample 1 is taken as the standard one. Then the percentage of the deviations of the mesh qualities of the 64 samples from the standard one based on the following equation is calculated as follows. Figure 6-12 is the percentage deviations of the mesh quality for three different domains. There are 64 different ways of formulating the initial conditions for each domain. It can be seen from Table 6-2 and Figure 6-12 that different initial conditions for generating mesh for the three domains make the final mesh quality different. That means small changes of formulating the design problem may lead to various changes on the results of the design solution. It can be implied that formulating the design problem differently may increase the chance of generating creative design solutions.

$$\text{Percentage of deviations} = \frac{|\,\text{mesh quality of sample}i - \text{mesh quality of sample}1\,|}{\text{mesh quality of sample}1} \times 100\%$$

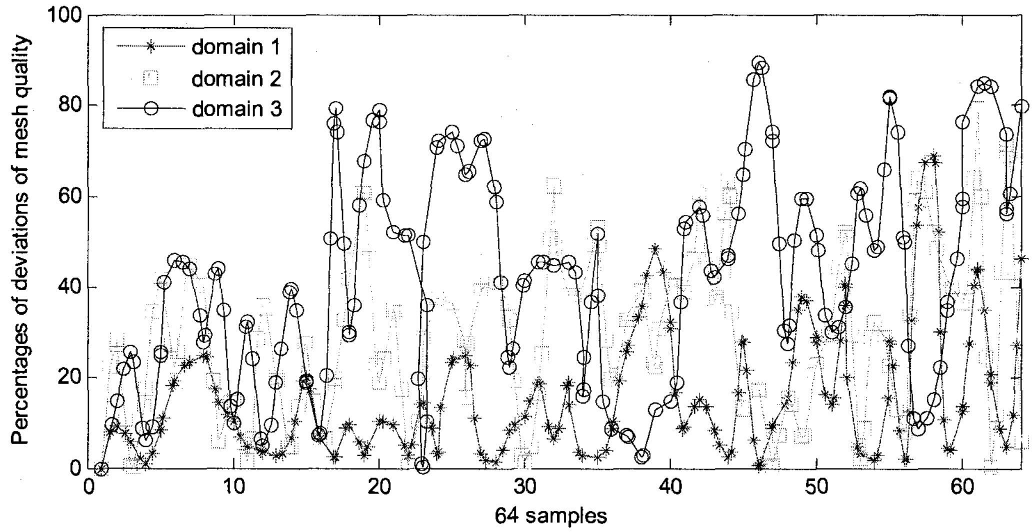
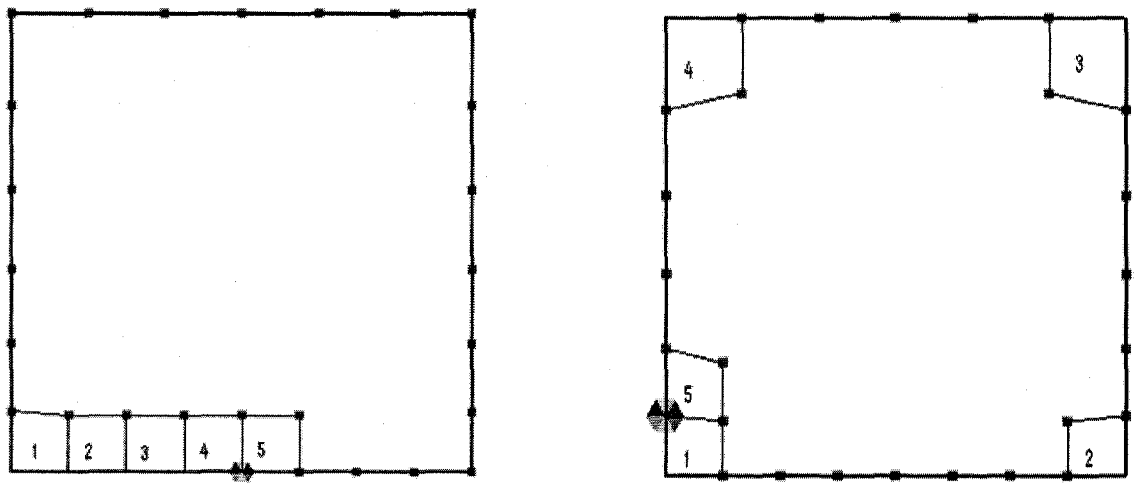


Figure 6-12 Deviations of mesh quality for three domains

6.4.2 Sequence of decomposition of design problem

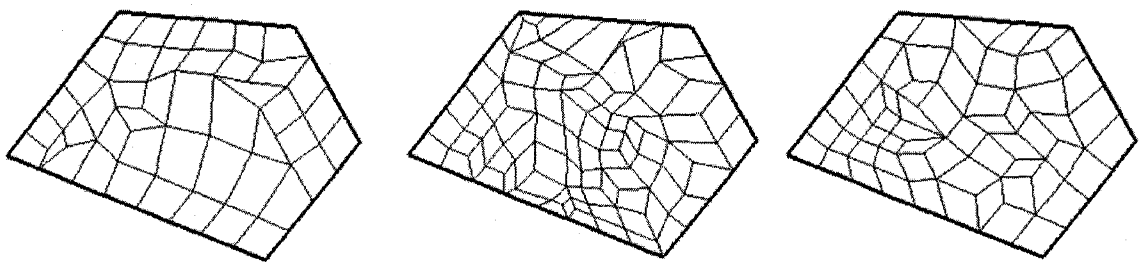
The decomposition of the mesh generation problem is to decompose the current boundary for generating an element around a reference point from the boundary. A reference point is where to start to decompose the boundary and extract an element, but not every point on the existing boundary can be taken as a reference point. In this study, if the angle at a boundary point is between 45° and 135°, it may be taken as a reference point. Once a new element is generated, the next reference point needs to be selected. The sequence of decomposition of design problem in the example of mesh generation is to find a way to identify a reference point. Various criteria can be used to identify the next reference point. Figure 6-13 shows two examples.



(a) (b)

Figure 6-13 Finding reference point: (a) newer boundary first; (b) older boundary first

The method in Figure 6-13 (a) always chooses the first valid reference point next to the current one from the updated boundary. In another method, the updated boundary will not be processed until all the valid reference points in the original boundary have been processed. This is shown in Figure 6-13 (b). In the Figure 6-13 (b), the first four elements are generated from the original boundary and element five is generated in the new boundary since no more points meet the requirements of a reference point on the original boundary. If no reference point has been found, then a quadrilateral element will be extracted around the shortest boundary segment. A third method is to randomly choose a valid reference point from the updated boundary for generating an element. Using the three different methods to find reference points to decompose the same domain, different meshes can be generated as shown in Figure 6-14.



(a) Older boundary first (b) Newer boundary first (c) Random boundary point

Figure 6-14 Three different ways of decomposition of mesh generation problem

Three different ways of decomposing the mesh boundary on 10 randomly generated domains have been tried based on the same initial conditions. One way analysis of variance (ANOVA) is used to evaluate the effect of the three different decomposition methods on the final generated mesh quality. The ANOVA results, as in Table 6-3 shows that the effect is significant ($F=4.93 > p=0.015$). Figure 6-15 shows the comparisons of the mesh qualities of 10 different mesh domains using three decomposition methods. It can be seen that method (a) can generate better mesh quality than method (b) and (c). This is because method (a) considers more boundary information by choosing all possible reference points from the original boundary and updates the original boundary with all newly generated elements. However, with method (b), the local boundary will become bad with the appearance of a bad element and continues to generate bad elements; and method (c) is to randomly choose a reference point on the boundary and it cannot guarantee to generate good elements. In the mesh generation problem, method (a) can be a good way for generating high quality mesh. Therefore, changing the sequence of decomposition of design problem may lead to different design solutions.

Table 6-3 One way ANOVA table

ANOVA Table

Source	SS	df	MS	F	Prob>F
Columns	0.01417	2	0.00708	4.93	0.015
Error	0.03883	27	0.00144		
Total	0.053	29			

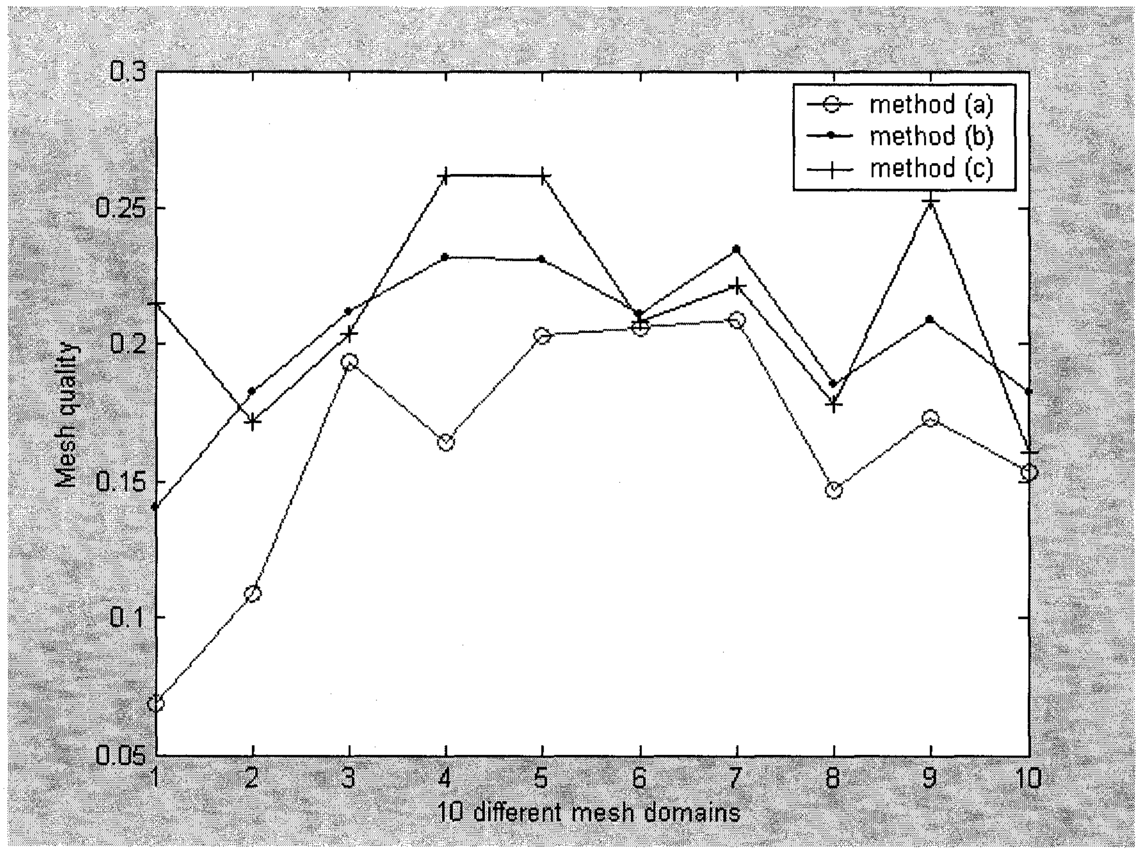


Figure 6-15 Comparisons of mesh qualities using three decompositions methods.

6.4.3 Synthesis knowledge

The element extraction method is used in the mesh generation problem. The element extraction method repeatedly generates elements within the domain using some predefined “if-then” rules until the whole domain is filled with required elements. There are three basic rules to extract an element from the domain shown in Figure 6-16. The solid lines represent three basic boundary features and the dashed lines are the added lines to form an element based on the boundary features. The rule #2 is most commonly used for dealing with the boundary features.

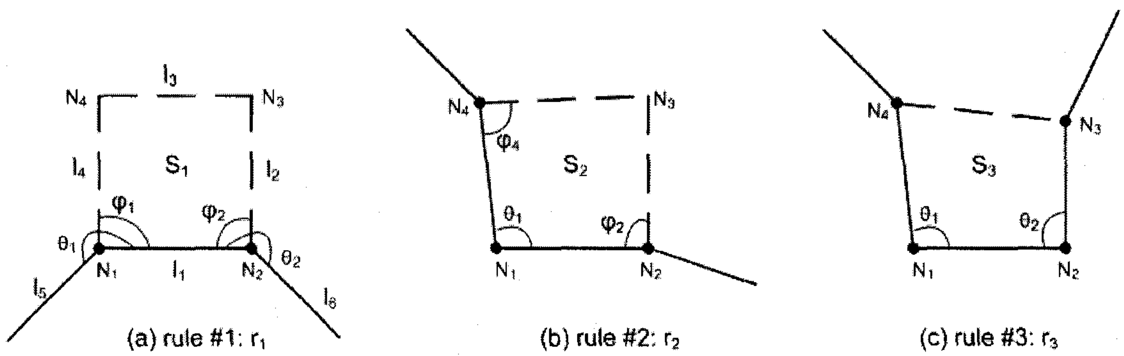


Figure 6-16 Three basic element extraction rules.

Zeng and Cheng (1993) developed five “if-then” rules for this system through an interactive trial-and-error process based on the basic element extraction rules. These five rules represent synthesis knowledge for generating an element. For the five heuristic rules, each rule is developed based on the special features of the boundary, so the mesh can be generated better with combining more heuristic rules. Figure 6-17 shows an example using different rules to generate mesh elements. In Figure 6-17 (a), around the boundary points, 1, 2, 3, 4, (b) gives the result of a bad element using three rules, but (c) shows a good element using five rules. With the appearance of the bad element, the succeeding elements cannot be generated well.

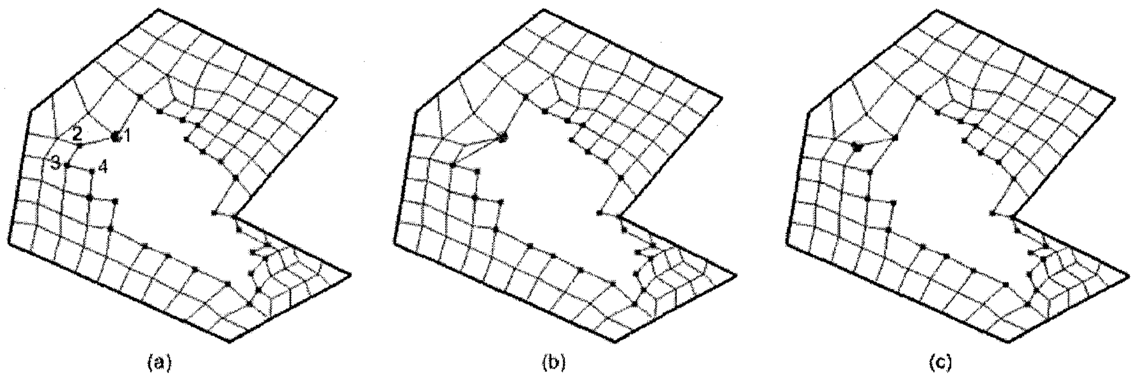


Figure 6-17 Comparisons of mesh results using different rules.

The five rules used in the mesh generation design problem are different and each can represent different designers with different synthesis knowledge. Among these rules, rule 5 is an essential rule to generate an element. So one rule (rule 5), three rules (rule 3, rule 4 and rule 5), and five rules are taken to generate mesh elements on the same domain respectively. 10 domains with complex boundary features are selected and one rule, three rules and fives rules are applied on the 10 domains for mesh generation. It can be found out more good elements can be generated when increasing the number of the rules. If the bad elements are generated using fewer rules, the succeeding mesh elements cannot be completed well. Figure 6-18 shows the generated mesh elements using one rule, three rules and five rules.

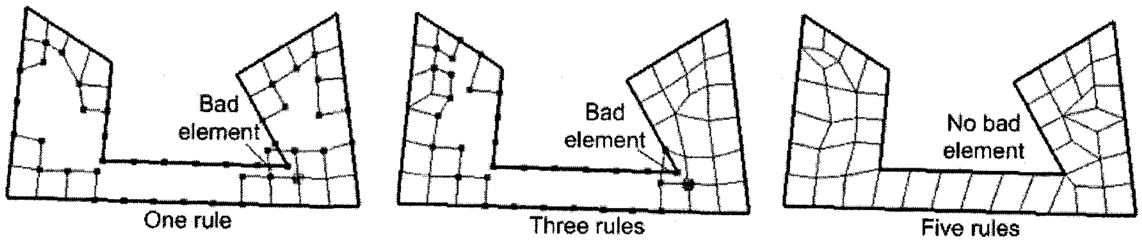


Figure 6-18 Comparisons of bad elements using different rules.

Then, the number of the elements generated before the appearance of a bad element is counted using one rule, three rules and five rules on the 10 different domains, as shown in Figure 6-19. It can be seen that with more number of rules used in mesh generation, more good elements can be generated. Therefore, extending the synthesis knowledge can increase the chance of getting good design solutions.

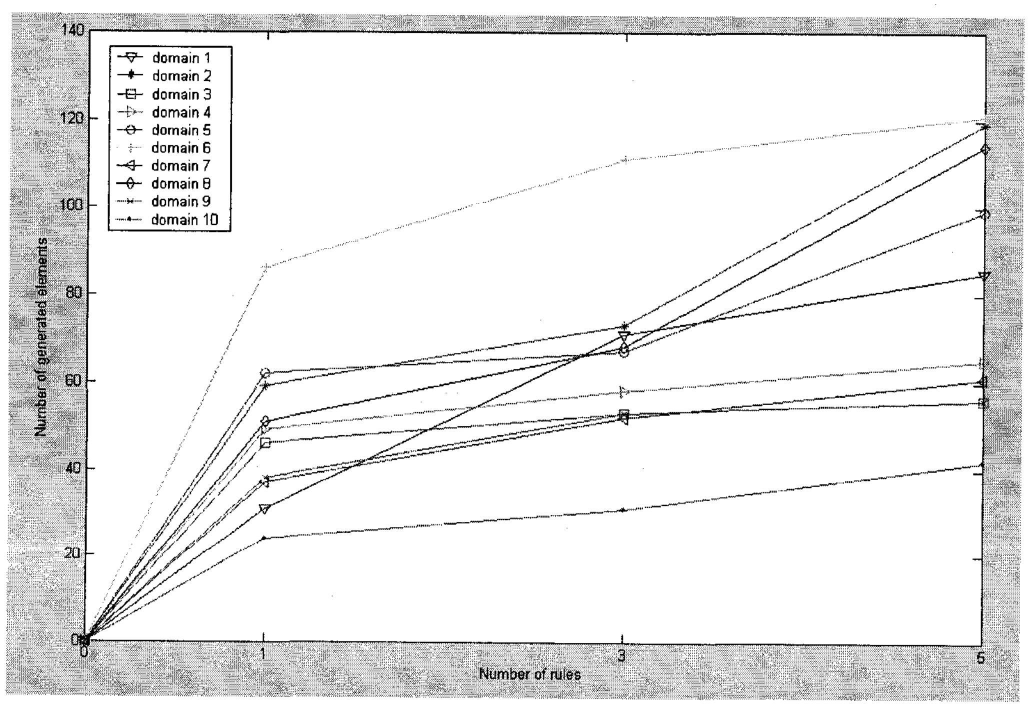


Figure 6-19 Number of generated elements using different rules for ten domains.

6.5 Concluding Remarks

The experiment results showed how to examine the three hypotheses observed from environment-based design model and design phenomena based on a mesh generation design problem. In using the model of EBD, three elements are important: primitive synthesis knowledge, primitive environment and primitive solutions. Based on the three elements, three strategies were given for creating different design solutions: formulating design problems differently, changing the sequence of decomposition of the design problem and extending synthesis knowledge. The experimental results conclude that, changes in problem definition, problem decomposition, and synthesis rules can change the final design solutions. Increasing the possibilities of generating different design solutions may increase the chance of getting creative design solutions. So far as the author knows, this is the first attempt that the virtual experiment is used in the area of product design to investigate design activities (Yao 2007d). Many other design phenomena or properties can be also verified using the virtual experiment.

Chapter 7
Application: Development of an ANN-Based Element Extraction Method

7.1 Introduction

A finite element mesh is a discretized representation of a geometric domain. A domain is discretized into elements, which may be triangles, quadrilaterals, tetrahedron, or hexahedron. Although many mesh generation methods and algorithms have been developed (Sadek 1980; Brown 1981; Woo 1984; Yerry and Shephard 1984; Cavendish et al. 1985), The mesh generation of geometric shapes with complex boundary is still an open question (Shewchuk 2002). Element extraction is recognized as a flexible method to solve mesh generation design problems (Saxena and Perucchio 1990). The element extraction method repeatedly generates element (s) within the domain using some predefined "if-then" rules until the whole domain is filled with required elements. The meshes generated by this method usually have high quality elements in the area close to the geometric boundary. This is a feature which is critical for complex engineering problems (Cavalcante Net 2001). However, the "if-then" rules for element extraction are usually difficult to acquire since the acquisition of these element extraction rules is usually done through an interactive trial-and-error process. The success of this interactive process largely depends on the insight and luck of the algorithm developer. The difficulty of this approach is reinforced as the complexity of the problem rises. An automatic rule acquisition method would be essential and even indispensable for the element extraction method to be applied to a wider range of problems.

Artificial Neural Network (ANN) can be such a method used to learn the element extraction rules for automatic mesh design. The artificial neural network is used to represent the "if-then" element extraction rules and to train the relationship behind these rules. As shown in Figure 7-1, the input for the network is the geometry domain boundary while the output is the generated mesh elements filled in the domain. So, the design problem in this chapter is to develop an ANN-based element extraction method to automatically extract quadrilateral mesh elements from a two-dimensional geometry domain. The requirements for the generated mesh elements are the same as described in Section 6.3.2.

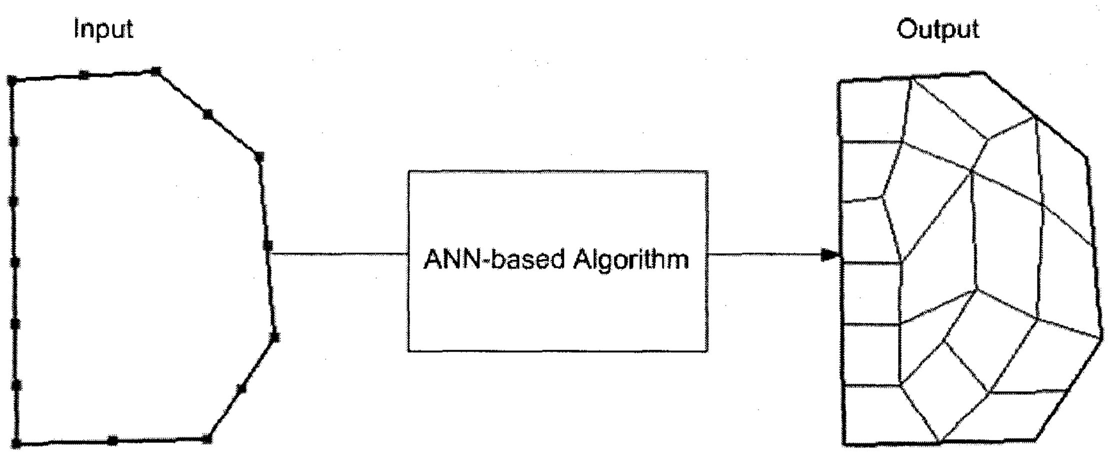


Figure 7-1 Input and output of the ANN-based algorithm

In order to generate good quality elements while keeping the updated problem still solvable, the design and definition of the neural network is more complex than those in the traditional classification problems. The process flow of the environment-based design model is applied on this design problem to generate the procedure of the ANN-based algorithm. The three routes leading to new designs validated in Chapter 6 are employed as strategies to solve the conflicts identified in the development of the ANN-based algorithm.

The rest of this chapter gives the details of developing this ANN-based element extraction method for finite element mesh design problem. Section 7.2 introduces the algorithm and system architecture. The definition and collection of training samples are explained in Section 7.3. Section 7.4 analyzes the results of the developed algorithm and gives some discussions. Finally concluding remarks are given in Section 7.5.

7.2 ANN-Based Element Extraction: Algorithm and System Architecture

The design problem is to develop an ANN-based element extraction method to automatically extract quadrilateral mesh elements from a two-dimensional geometry domain. Environment-based design methodology (EBD) is employed to generate the algorithm. EBD includes three main stages: environment analysis, conflict identification, and concept generation. The input for this network includes the coordinates of some boundary points while the output defines the parameters for extracting an element. Both the input and the output are taken as environment components. The product to be designed is the ANN-based algorithm to represent the relationship between the input and the output. Considering the relationships between the input, output, and the algorithm, the first conflict is how the algorithm can represent the relationship between the input and the output. A neural network is an interconnected group of nodes, akin to the vast network of neurons in the human brain (http://en.wikipedia.org/wiki/Artificial_neural_network). So the concept from the conflict is to define the structure of neurons to represent the input and output and the algorithm to represent the connections between neurons. Considering neurons, connections, previous environment components and their relationships, another conflict is how the neurons and connections can capture the information between the input and output. The concept for the conflict is to train the neural network model using the initial training samples. Once the neural network is trained, the weights and bias between neurons can represent the relationship between input and output, and then the neural network model can be applied to extract new mesh elements. If the generated mesh elements are not good enough, the conflict exists between the algorithm and the mesh elements. This conflict can be solved by adjusting the algorithm using adjusted training samples until the generated elements are good. When the number of points on the boundary is less than the number of defined input points, it is a final pattern and the ANN algorithm cannot be applied to solve the final pattern. Specific considerations need to be figured out to solve the final pattern conflict.

The design problem of developing an ANN-based algorithm has been analyzed using the main steps of environment-based design. The description of the algorithm and the structure of the neural network will be introduced in Section 7.2.1 and Section 7.2.2 respectively. A final pattern will be explained in Section 7.2.3. The definition and collection of the training samples will be elaborated in Section 7.3.

7.2.1 Description of the algorithm

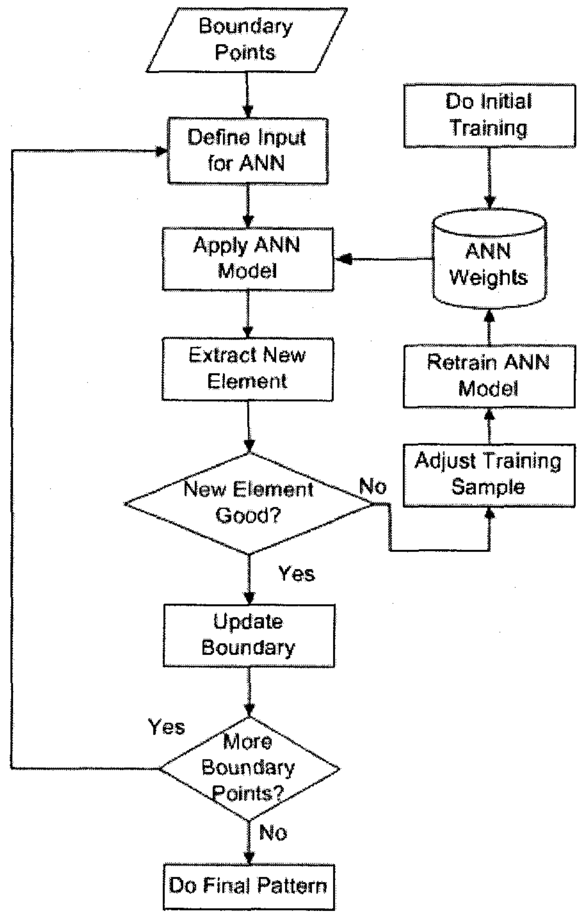


Figure 7-2 Flow chart of ANN-based mesh generation.

The procedures of the ANN-based mesh generation are outlined in Figure 7-2. An ANN model is trained to identify the relationship between input and output using initial training samples. Training of the ANN model is referred as the calculation of the weight matrix and the bias terms between neurons in different layers. In this study, Back-Propagation (BP) learning algorithm is adopted for the training (Khanna 1990). Details on the definition of collecting training samples will be elaborated in Section 7.3. To generate a finite element mesh, a point is chosen from the existing boundary points. This point is called a reference point, around which the new element is generated. A reference point is where to start to extract an element, but not every point on the existing boundary can be taken as a reference point. In the present study, if the angle at a boundary point is between 45° and 135°, it may be taken as a reference point. Once a new element is generated, the next reference point needs to be selected. Section 6.4.2 has discussed three different strategies to choose a reference point and found out method (a) as shown in Figure 6-14 can be a good way for generating high quality mesh since this method considers more boundary information by choosing all possible reference points from the original boundary and updates the original boundary with all newly generated elements. Hence, method (a) is used as the sequence for choosing the reference point. Around the reference point, a number of points (called leading points) that have more influence than others on generating a new element are collected from the existing boundary. The input data including the coordinates of the reference point and its corresponding leading points are then fed into the initially trained ANN model. The output of the ANN model is the parameters that can represent the new element to be extracted. According to the output parameters, a new element is extracted around the reference point. If the new element is not good enough, the training samples will be adjusted and the ANN model will be retrained until a good quality element is extracted. Then the boundary will be updated for generating the next element. This procedure is repeated until the final pattern is satisfied on the existing boundary. The considerations for the final pattern will be explained in Section 7.2.3.

7.2.2 Structure of the ANN for element extraction

The input for element extraction is a set of boundary components and the output is the new element to be extracted. A general input-output relation is shown in Figure 7-3. In the figure, a new element is extracted around a reference point P_0. To generate an element around a reference point, all the geometric features that constrain this element should be taken into account as the input. The ideal situation is to take all existing boundary points and their mutual relationship as the input. However, this is computationally expensive and it is practically impossible to define generic element extraction rules. Too many points in the input of an ANN model means that a domain with the less number of points than that of the input points in the ANN will have to be processed with other methods. This situation may be further complicated by the complex relationships behind large number of points. A trade-off is to take into account a certain number of leading points from the existing boundary that play a significant role in generating an element around the reference point.

In Figure 7-3, 2N points are picked up around a reference point as the leading points. The number of leading points is selected based on the complexity of the domain. Theoretically, the more complicated is the domain, the more leading points will be included for the input data. The coordinates of the leading points together with the reference point constitute the input of the neural network model as

$[P_{(l,N)}, P_{(l,N-1)}, \cdots P_{l2}, P_{l1}, P_0, P_{r1}, P_{r2}, \cdots, P_{(r,N-1)}, P_{(r,N)}]$. In this study, four leading points and one reference point are chosen as the input data denoted by $[P_{l2}, P_{l1}, P_0, P_{r1}, P_{r2}]$.

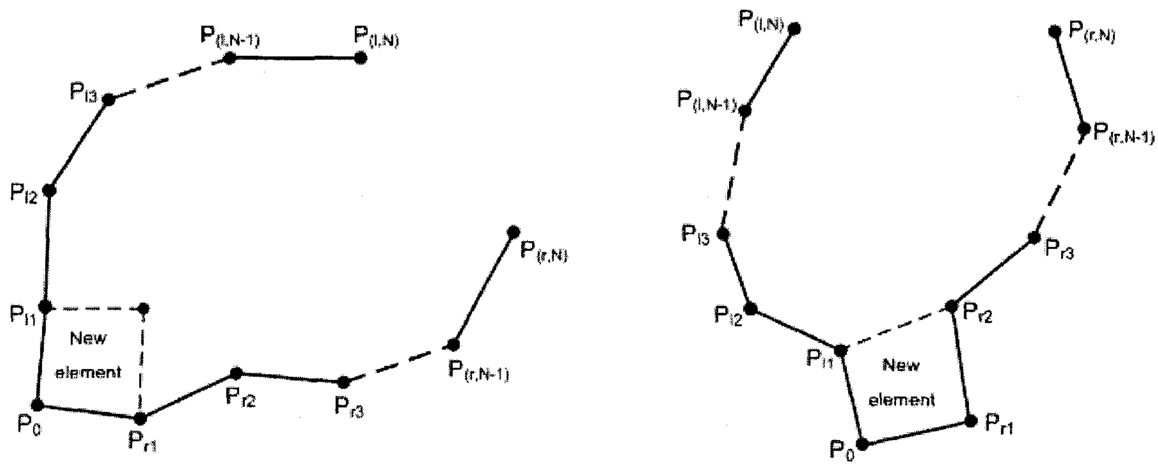


Figure 7-3 Leading points.

The output includes the parameters to define a new element. In this study, three types of extractions are considered as shown in Figure 7-4. Type 0 represents the case where an element is extracted by adding a new point on the base of three boundary points. Type 1 and 2 represent the case where an element is extracted without adding any new point. The difference between type 1 and type 2 is the relative location of the reference point. Type 1 has the reference point on the left corner of the element whereas Type 2 has its reference point on the right corner of the element. $[\text{type}, P_n]$ is used to represent a new element. The variable "type" should take the values of 0, 1, and 2. P_n is the newly generated point in the new element for Type 0. There is no new point generated for Type

1 and 2, but the opposite point of the reference point as P_n circled in Figure 7-4 is included to keep the components of all the output consistent. For the convenience of succeeding description, P_n is called output point.

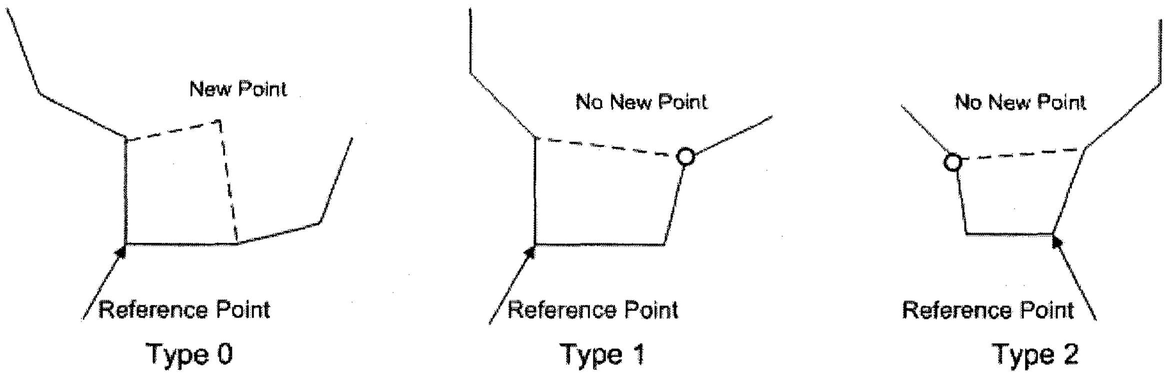


Figure 7-4 Three types of new elements.

Based on the discussions above, the architecture of the ANN for element extraction is shown in Figure 7-5. It is indeed a transformation as follows:

$$[\text{type}, P_n] = f([P_{(l,N)}, P_{(l,N-1)}, \cdots P_{l2}, P_{l1}, P_0, P_{r1}, P_{r2}, \cdots, P_{(r,N-1)}, P_{(r,N)}]) \tag{7-1}$$

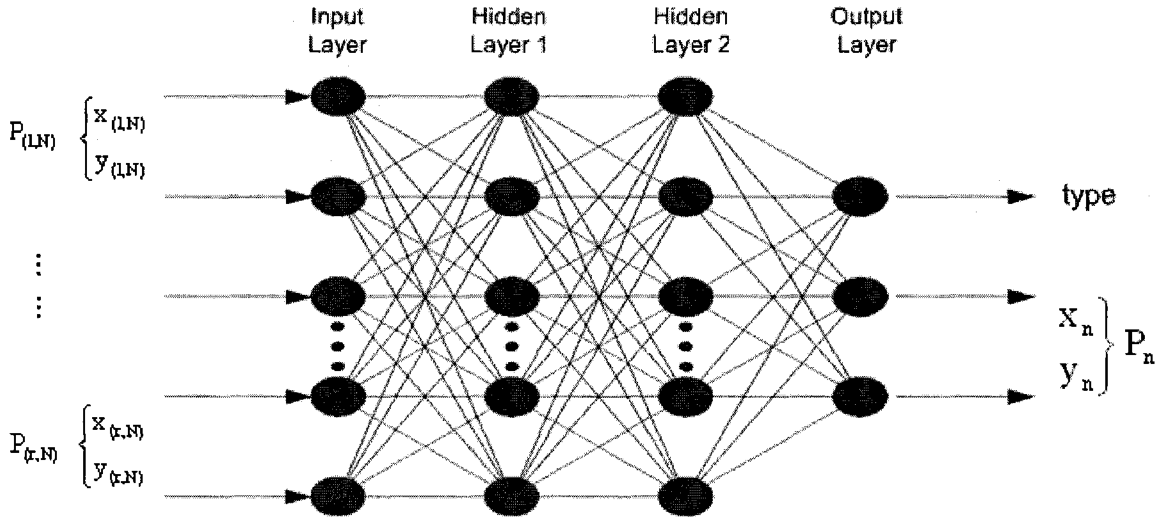


Figure 7-5 ANN model structure.

7.2.3 Final pattern

A final pattern is needed when the number of points left on the boundary is less than the number of input points in the neural network. If five boundary points are used to extract a new element, then the last boundary will have four points left, which form a quadrilateral element. Thus, no final pattern is needed. For seven points taken as the input, however, there are only six points left on the last boundary. These six points have to be dealt with separately. For this final pattern, three situations will be considered to complete the mesh generation as shown in Figure 7-6 (Zeng and Cheng 1993).

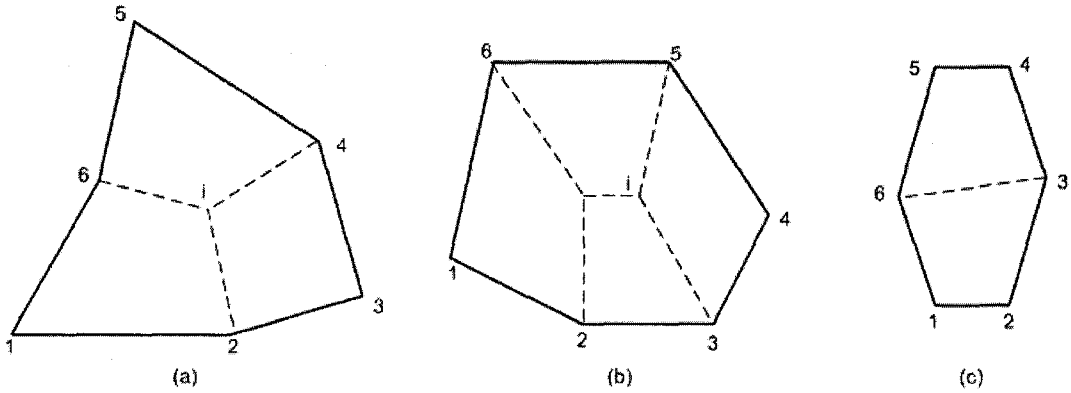


Figure 7-6 Final patterns.

For the pattern shown in Figure 7-6 (a), the coordinates of the i th node is

$$\begin{cases} x_i = \frac{1}{3}(x_2 + x_4 + x_6), \\ y_i = \frac{1}{3}(y_2 + y_4 + y_6). \end{cases} \tag{7-2}$$

For the pattern shown in Figure 7-6 (b), the coordinates of the i th node is

$$\begin{cases} x_i = \frac{1}{8}(3 * x_3 + 3 * x_5 + x_2 + x_6), \\ y_i = \frac{1}{8}(3 * y_3 + 3 * y_5 + y_2 + y_6). \end{cases} \tag{7-3}$$

For the pattern shown in Figure 7-6 (c), connect point 3 and point 6.

It should be noted that if nine points or more are used as the input to extract a new element, the final pattern becomes more complex since more different situations have to be taken into account to complete the mesh generation.

7.3 Definition and Collection of Training Samples

A key issue in applying artificial neural network is the definition and collection of training samples. The training samples have to be representative and inclusive so that the training results can be extrapolated to other problems. This is especially critical for mesh generation. Unlike general classification problem, ANN-based element extraction method will repeatedly apply the same neural network, by which the original problem is redefined every time. A badly trained neural network may soon generate a boundary that is out of the scope defined by the primitive boundary components.

7.3.1 Generation of training samples

Once the structure of ANN model is determined, a set of training samples can be used to train the ANN model. Theoretically, the training samples should include all possible patterns underlying different combinations of input and output. However, it will be tedious and time-consuming to generate all the patterns. This study proposes a self-learning method that adjusts the training samples by adding new patterns into the initial training samples. First, a set of training samples are used to represent the basic patterns to train the ANN model. If the ANN model with the initial training samples fails to generate a good element that belongs to another pattern, then the training samples are adjusted by adding samples of another pattern. The retrained ANN model will be used to generate elements. As shown in Figure 7-7, the procedure will be repeated until a good element is generated.

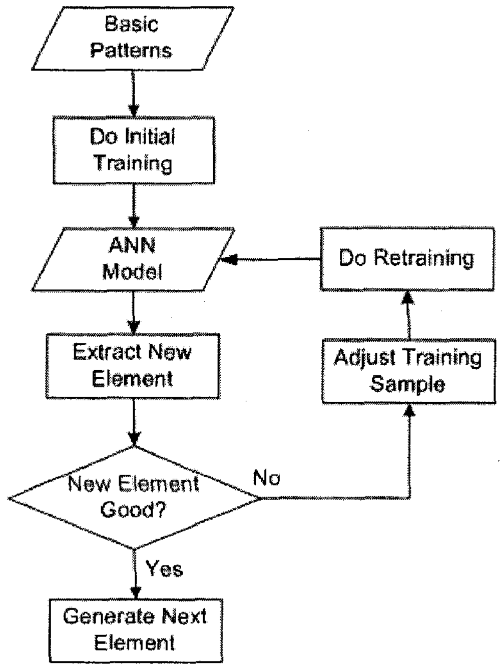


Figure 7-7 Procedure of retraining of ANN model.

7.3.2 Initial training samples

The initial training samples should combine the basic relationship of input and output. This research ignores the influence of the relative length of boundary components and considers only three levels (small, medium and large) of angles. The angle of small level is between 0° and 90°; the angle of medium level is between 90° and 180°; and the angle of large level is between 180° and 270°. Therefore, there are $3^{(n-2)}$ different patterns given n leading points. In this present study, four leading points are used. As a result, there are $3^2 = 9$ patterns as shown in Figure 7-8. Obviously, pattern 5 is not a valid one; so, no initial training samples will be generated for this pattern. For each of other patterns, a different angle is used at the reference point to generate a number of training samples. For example, Figure 7-9 shows the different forms of pattern 1. It should be noted that the number of training samples for each pattern is the same. With equal number of samples, each pattern will play an equal role in the training of the ANN model.

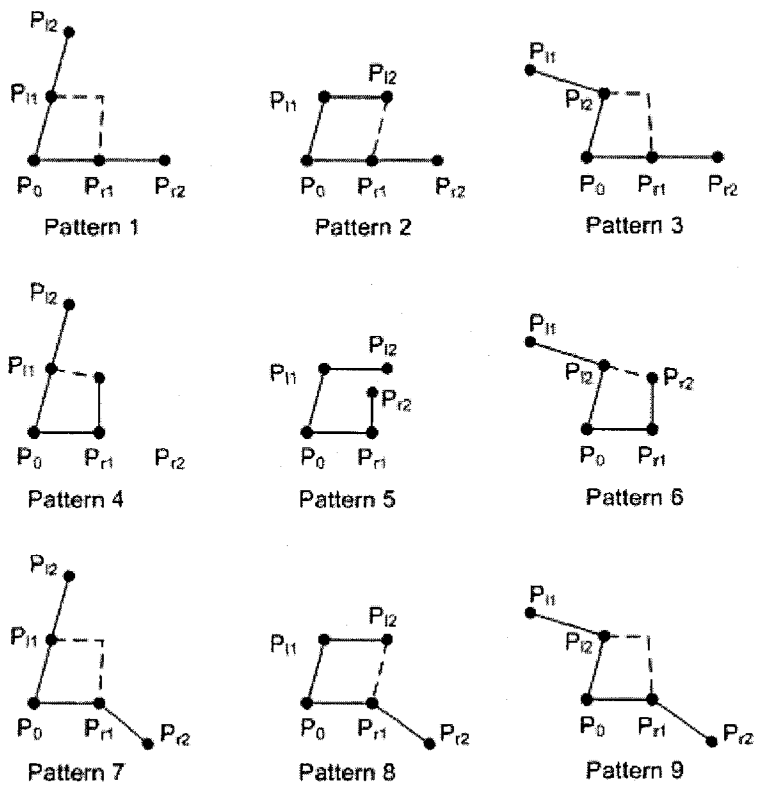


Figure 7-8 Nine patterns of input-output relationship.

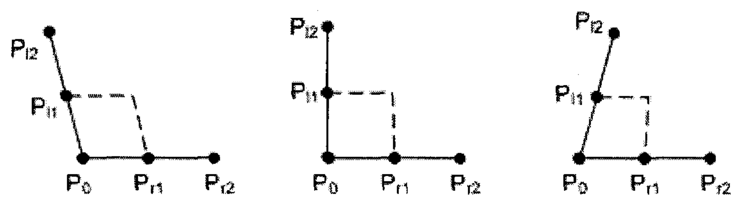


Figure 7-9 Different forms of pattern 1.

7.3.3 Collection of training samples

To generate a training sample from an existing mesh, a set of points including leading points, reference point and the output point can be manually as well as automatically picked up. A user interface has been designed to pick up training samples. Figure 7-10 shows the three types of training samples that can be collected from a mesh. Five points P_{l2}, P_{l1}, P_0, P_{r1}, and P_{r2} are collected from left to right and the output point is chosen as P_n. It should be noted that the new point P_n is P_{r2} in Figure 7-10 (b) and the new point P_n is P_{l2} in Figure 7-10 (c). The coordinates of the six points and the type of the new element will be taken into a training sample. Any mesh with good quality elements may be used for the collection of training samples. Table 7-1 gives an example of ten collected training samples.

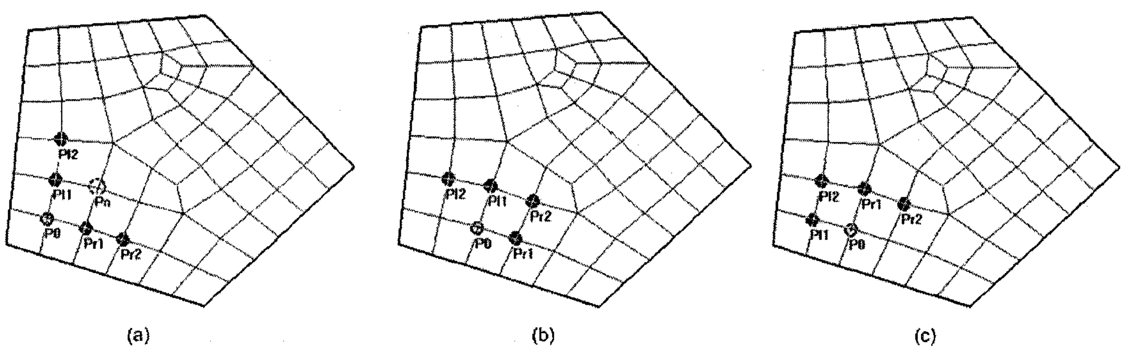


Figure 7-10 Three types of patterns collected for training samples: (a) type 0; (b) type 1; (c) type 2.

Table 7-1 Examples of training sample

Input										Output		
x_{l2}	y_{l2}	x_{l1}	y_{l1}	x_0	y_0	x_{r1}	y_{r1}	x_{r2}	y_{r2}	*type*	x_n	y_n
-1.19747	-1.71510	-1.10663	-2.10847	-1.01492	-2.66143	-0.56218	-2.54597	-0.11065	-2.43125	0	-0.65359	-2.08499
7.09138	3.45006	7.19690	2.97116	7.30200	2.49023	7.75940	2.58950	8.21746	2.68208	0	7.65880	3.06881
-1.31411	-22.26263	-1.18250	-22.75125	-1.05347	-23.23812	-0.54303	-23.13958	-0.01878	-22.99969	0	-0.69559	-22.65612
28.87224	-16.62693	28.92887	-17.12498	28.97799	-17.59023	29.24159	-18.02599	29.56558	-17.63935	0	29.35953	-17.43713
-0.83000	-1.15982	-0.74299	-1.62316	-0.65359	-2.08499	-0.20275	-1.98309	-0.29120	-1.53371	1	-0.29120	-1.53371
90.36793	-77.08303	91.75735	-77.30490	91.40188	-78.55770	92.68953	-78.78819	93.05584	-77.56182	1	93.05584	-77.56182
8.12956	-1.27602	8.54664	-1.07961	8.68724	-1.51258	9.11806	-1.29582	8.95484	-0.87355	1	8.95484	-0.87355
-0.36940	-93.02264	-0.16822	-93.50457	0.32499	-93.32099	0.11808	-92.93960	-0.07805	-92.36122	2	-0.36940	-93.02264
28.24149	-15.77552	28.31361	-16.25464	28.80012	-16.14801	28.72781	-15.66914	29.21343	-15.56651	2	28.24149	-15.77552
10.78457	1.51536	10.87277	0.94707	11.40918	1.11712	11.35253	1.69310	11.93000	1.78592	2	10.78457	1.51536

7.3.4 Normalization of input and output

It can be found from Table 7-1 that the coordinates of points for input and output data could be any values. However, what matters between input and output are the relative positions of all points in each sample. Furthermore, it is this relative position that can be applied independent of the problems from which the samples were collected. To capture the generic relationship between these points, it is essential to transform all the coordinates into a uniform coordinate system without distorting the relations among the input and output. In the two-dimensional quadrilateral mesh generation problem, the reference point is taken as the origin of the new coordinate system. The vector from the reference point to the first leading point on the right side of the reference point is set as a unit vector along the positive direction of x axis. All the points in each sample are then transformed into this new coordinate system by translation, scaling and rotation. This is shown in Figure 7-11.

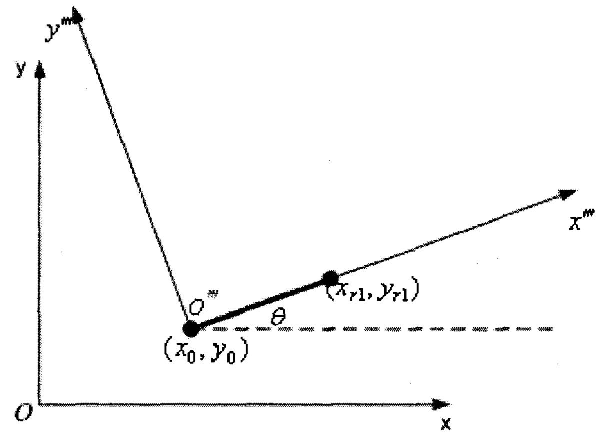


Figure 7-11 Coordinate transformation.

Given the reference point (x_0, y_0) and the first leading point on the right, (x_{r1}, y_{r1}), the new coordinate system $X'''O'''Y'''$ is shown in Figure 7-11. All the points including leading points, reference point, and the output point in the new element in each sample will be transformed into the new coordinate system $X'''O'''Y'''$.

A. Translation

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} -x_0 \\ -y_0 \end{pmatrix}. \tag{7-4}$$

B. Scaling

$$d = \sqrt{(x_0 - x_{r1})^2 + (y_0 - y_{r1})^2},$$
$$\begin{pmatrix} x'' \\ y'' \end{pmatrix} = \begin{pmatrix} 1/d & 0 \\ 0 & 1/d \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix}. \tag{7-5}$$

C. Rotation

$$\begin{pmatrix} x''' \\ y''' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x'' \\ y'' \end{pmatrix}. \tag{7-6}$$

Using homogeneous coordinates, this transformation can be represented as

$$\begin{Bmatrix} x''' \\ y''' \\ 1 \end{Bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1/d & 0 & 0 \\ 0 & 1/d & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -x_0 \\ 0 & 1 & -y_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x \\ y \\ 1 \end{Bmatrix}. \tag{7-7}$$

The coordinates of the ten training samples after the coordinate transformation are shown in Table 7-2. As can be seen from the table, the coordinates of P_0 and P_{r1} remain the same for all samples. In this way, the coordinates of all the sampling points are defined in the same scale and their relationships are also standardized. The actual input for the neural network is also reduced to the coordinates of three points.

Table 7-2 Examples of training sample after transformation

Input										Output		
x'''_{l2}	y'''_{l2}	x'''_{l1}	y'''_{l1}	x'''_0	y'''_0	x'''_{r1}	y'''_{r1}	x'''_{r2}	y'''_{r2}	*type*	x'''_n	y'''_n
0.1219	2.0591	0.0599	1.0294	0	0	1	0	1.9971	-0.0009	0	1.0542	1.0044
-0.0048	2.0995	-0.0015	1.0518	0	0	1	0	1.9983	-0.0143	0	1.0072	1.0463
-0.1366	1.9374	-0.0662	0.9666	0	0	1	0	2.0412	0.0731	0	0.8881	0.9687
-1.7259	0.8013	-0.8322	0.3907	0	0	1	0	0.6797	0.9373	0	0.1305	0.7966
0.0690	2.0365	0.0316	1.0172	0	0	1	0	1.0277	0.9905	1	1.0277	0.9905
-0.3767	0.9704	0.0987	0.9906	0	0	1	0	1.1105	0.9722	1	1.1105	0.9722
-0.7873	0.9635	0.1587	0.9215	0	0	1	0	1.0977	0.9055	1	1.0977	0.9055
1.0464	0.9927	0.0498	1.0031	0	0	1	0	1.9866	-0.0166	2	1.0464	0.9927
0.9327	1.0257	-0.0673	1.0261	0	0	1	0	1.0598	-1.0231	2	0.9327	1.0257
0.7904	1.0067	-0.2017	0.9511	0	0	1	0	1.0619	-1.0087	2	0.7904	1.0067

7.4 Results and Discussions

7.4.1 Results analysis

In this study, the neural network model is trained with back-propagation (BP) algorithm. A sigmoid transfer function $f(x) = 1/(1+e^{-x})$ is used in the BP algorithm. The input data are four leading points and a reference point. The type of new element and the coordinates of the output point are taken as output data. Presently, there are no general rules to determine the number of hidden layers and the number of neurons on each hidden layer for optimal network architecture although there is some research work contributed in this area. This research developed the ANN architecture with 10 neurons on the input layer, 3 neurons on the output layer, and two hidden layers with 30 neurons in the first hidden layer and 18 neurons in the second hidden layer. Some numerical examples generated by this ANN method are shown in Figure 7-12 to display the mesh generation for different boundaries.

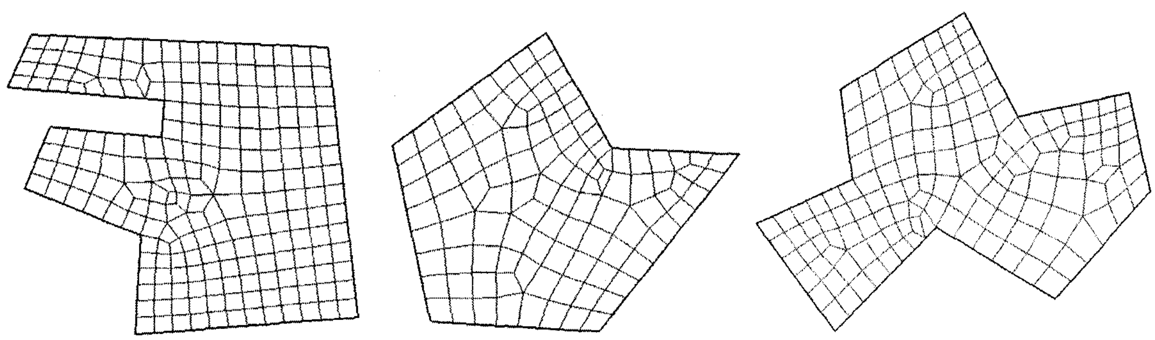


Figure 7-12 A few numerical examples generated by ANN method.

Element extraction method has the advantage of guaranteeing the quality of elements close to the domain boundary, but the disadvantage is also serious and obvious. To implement the element extraction method, this present study needs to consider the relationships of angles and segment lines to find the basic rules of creating an element based on local boundary features in a heuristic manner. The rules are used to reflect the relationship between boundary information and the element to be extracted. However, it is difficult to define the rules to generate a good-quality element based on all boundary information.

For the purpose of the study, ANN method attempts to solve the problems that element extraction method cannot deal with. The input of the ANN model is a set of leading points that represent the significant information of the existing boundary. The output is the parameters used to describe an element. Using ANN method, this present study no longer needs to develop basic rules to extract an element from the boundary feature manually. A number of training samples are used to learn the relationship between boundary information and the extracted element. One can decompose a complicated domain by correcting bad elements and adding more patterns into the training samples. In this way, mesh generation is a self-learning process by adjusting training samples. ANN method provides an alternative method in mesh generation.

Figure 7-13 shows a simple example and a complex example generated by the above two methods, respectively. The results show that the elements around the periphery are still good since the boundary feature is simple. When the boundary feature becomes complex in the center, the basic rules in the element extraction method still consider local boundary information, so they cannot continue to generate good-quality elements. However, the ANN method can continue to generate good-quality elements by adding more patterns into the training samples when the boundary condition becomes bad.

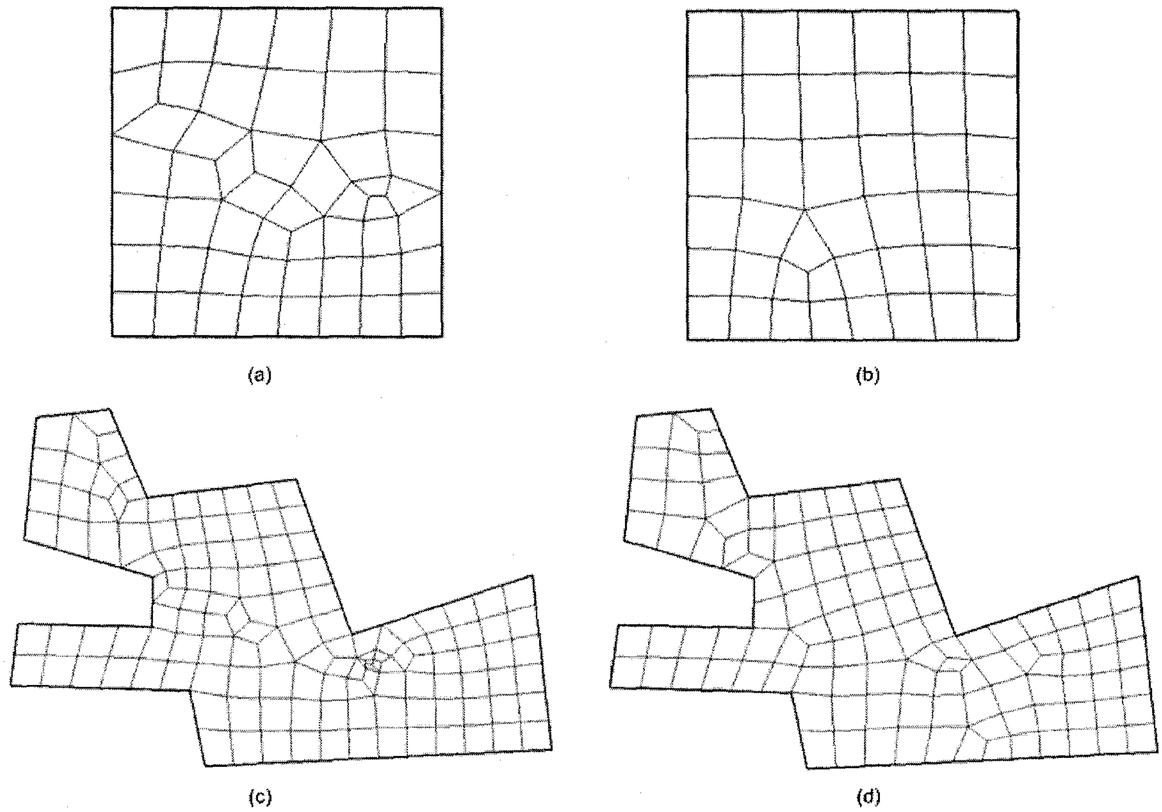


Figure 7-13 Mesh generation examples by element extraction method (a), (c) and by ANN method (b), (d).

In summary, the ANN method has its advantages over rule-based element extraction method in generating elements. First, using training samples, ANN model can learn the relationship between boundary points and the new elements. Secondly, mesh generation is a self-learning process by correcting bad elements and adjusting the training samples. Thirdly, this procedure can be theoretically extended for any mesh generation of 2D or 3D.

7.4.2 Influence of leading points

As mentioned earlier, the input of element extraction method includes the reference point and the corresponding leading points. Ideally, all the points on the existing boundary should be taken as the input data for generating a new element. However, too many nodes on the input layer will increase the time spent in generating training samples and training the ANN model. It also increases the difficulty in standardizing the input data and sorting out all the situations for the final pattern. The number of leading points must be made as few as possible. These leading points play a major role in extracting a new element, compared with other points on the existing boundary. The present study experimented with four and six leading points to decompose a 2D domain. For four leading points, eight basic patterns are used as shown in Figure 7-8 to generate a number of initial training samples. It should be noted that different forms of each pattern are included in the training samples and the number of training samples for each pattern is the same in order to make each pattern play an equal role in the training process. However, interactions also exist between patterns. Figure 7-14 shows an example of generating the first five new elements. By combining different patterns in the training samples, the deviations of the first five points are changing compared with those generated by the first pattern as shown in Figure 7-15. From the figure, it can be seen that the deviations of the first five points fluctuate with the increase of the number of patterns included in the training samples. So each new element in the final mesh generation is the mutual interactions of all the patterns in the training samples.

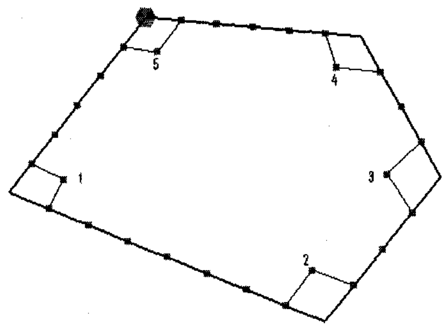


Figure 7-14 An example showing the generation of the first five elements.

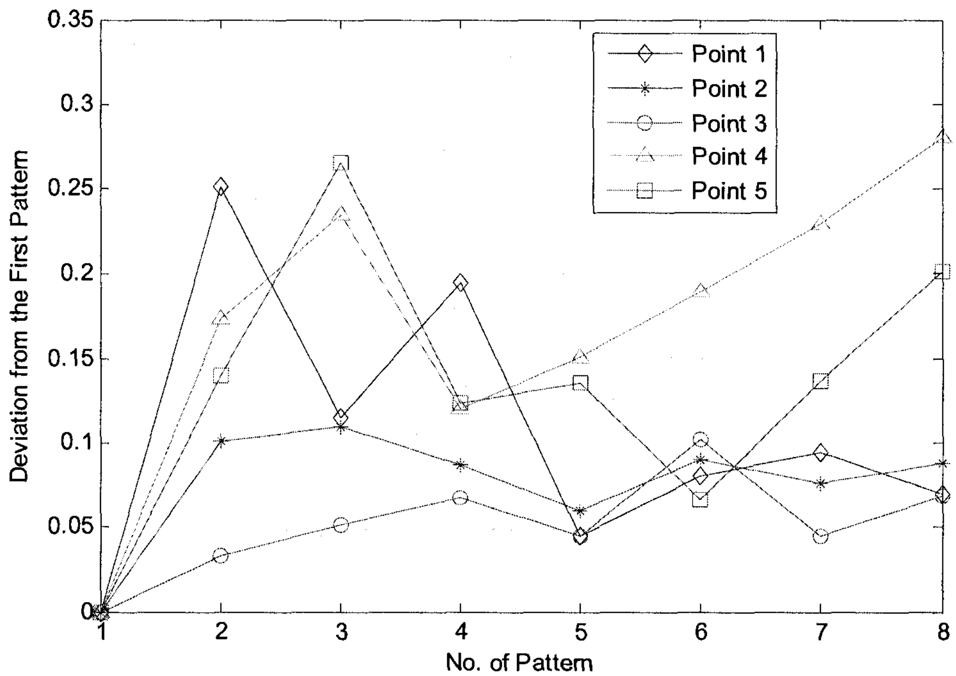


Figure 7-15 Deviations of first 5 points from first pattern for 4 leading points.

Using the initial training samples with these eight patterns, two bad elements are obtained as shown in Figure 7-16 (a). These bad elements are the result of the interactions of the initial patterns. To correct these bad elements, it is necessary to manually correct the bad element and add the pattern of the corrected element into the training samples. Meanwhile, more samples should be generated and added to the existing samples to enhance the impact of this pattern. Finally, the well-established mesh generation is shown in Figure 7-16 (b) after the ANN model is retrained.

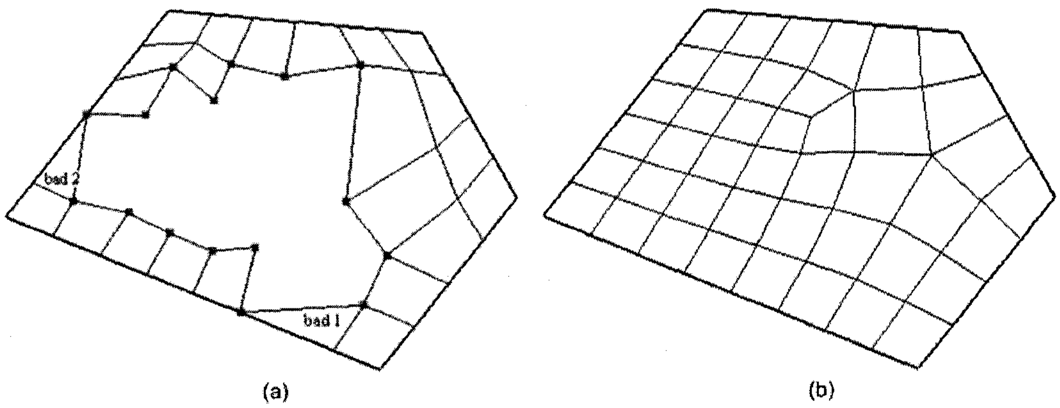


Figure 7-16 Mesh generation process of an example.

In the case of six leading points included in the input data, there are $3^4 = 81$ patterns. Although six leading points can include more information to generate better mesh, the work of generating all training samples for all 81 patterns is huge and tedious. The mutual interactions between these patterns would be greatly complicated. For the same example shown in Figure 7-14, Figure 7-18 shows the deviations of the first five new points generated by combining 8 patterns in the training samples from those generated by the first pattern. Compared with Figure 7-15, Figure 7-18 shows smaller deviations. This is because more boundary information has been considered in generating an element. Since eight patterns are only a small portion of all possible patterns, without the enumeration of all 81 patterns in the training samples, the final mesh generation is shown in Figure 7-17. The training samples for eight patterns do not include enough information to train the ANN model, which will generate poor elements in the situations that are not covered in the training samples. Figure 7-19 (a) and (b) show another example of mesh generation using four leading points and six leading points respectively. Obviously the mesh generation in Figure 7-19 (a) is more regular and more evenly distributed than that in Figure 7-19 (b).

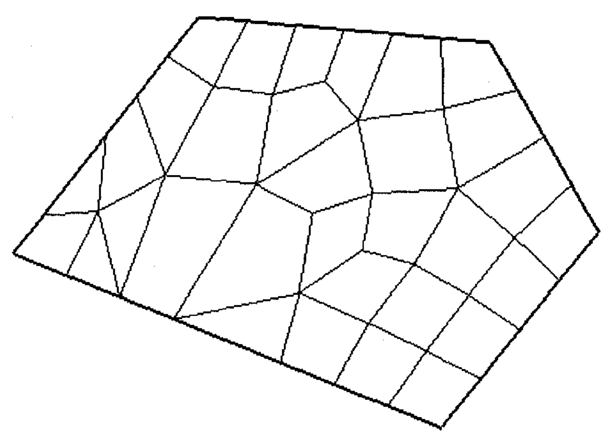


Figure 7-17 Mesh generation of the example by 6 leading points.

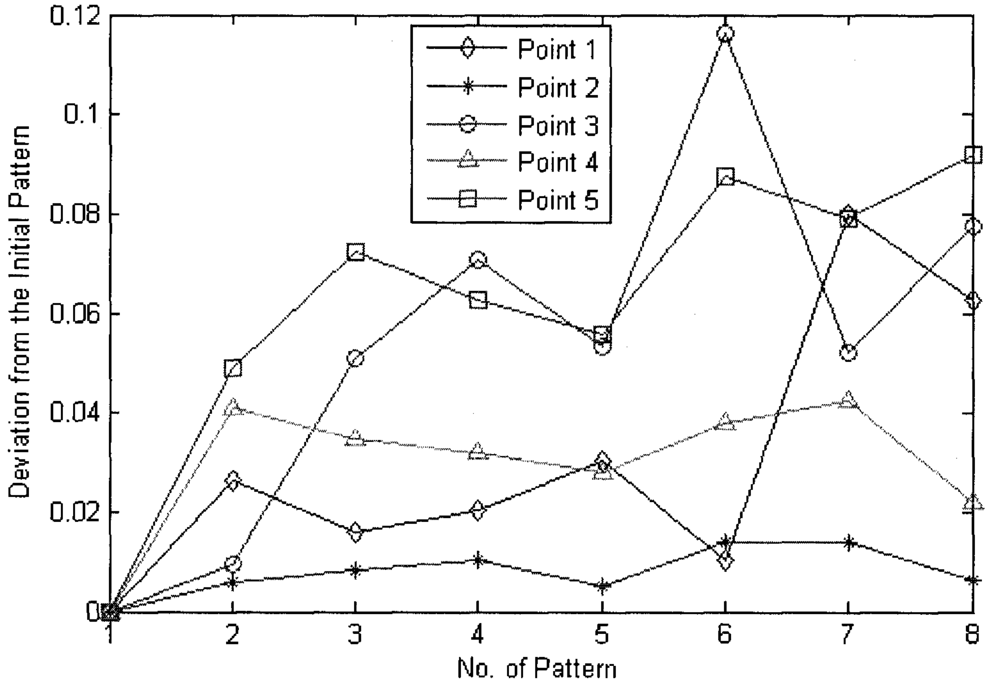


Figure 7-18 Deviations of First 5 points from First Pattern for 6 leading points.

From the results, it can be found that there are a small number of patterns for four leading points and it is easy to include all the patterns in the training sample. In contrast, the number of patterns for six leading points is too big to collect enough training samples and to guarantee good training results for the ANN model. Therefore, five boundary points (four leading points and one reference point) are used as the input data in the final system. If more leading points are used to decompose a more complicated domain, all the patterns or some representative patterns for these leading points have to be found out to generate a number of training samples.

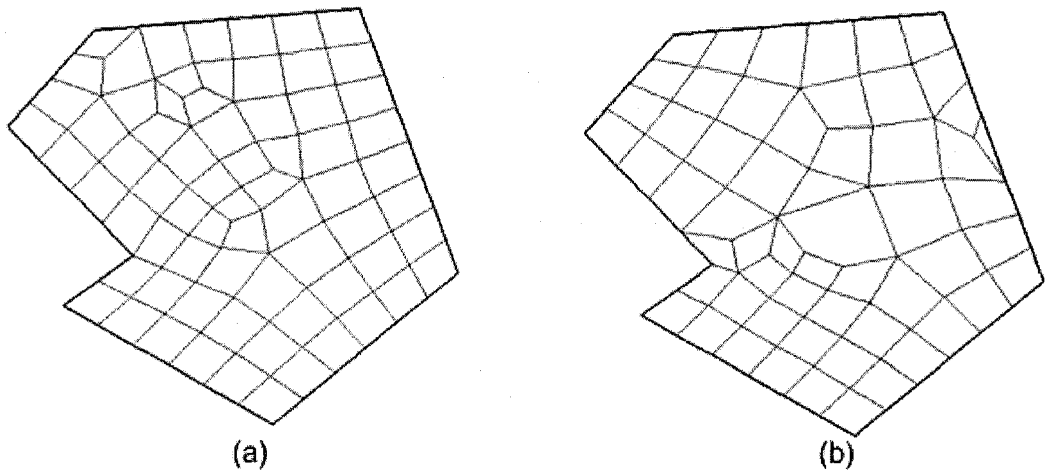


Figure 7-19 An example of mesh generation using different number of input points: (a) five input points; (b) seven input points.

7.4.3 Cognitive strategies used in ANN-based element extraction method

Rule-based element extraction method uses some heuristic rules summarized by experienced designers (Zeng 1992). However, this method can only be applied in solving some specific problems. To handle geometric shapes with complex boundary, a new ANN-based algorithm has been developed for solving finite element design in this chapter. The environment-based design is applied to analyze the design problem using the major steps, including environment analysis, conflict identification and concept generation. The three routes leading to new design validated by virtual experiment in Section 6 are used as cognitive strategies to solve some conflicts in the development of the ANN-based algorithm. The three routes are: formulating design problem differently, extending synthesis knowledge and changing the sequence of environment decomposition. Next are the details of how the cognitive strategies are used in the ANN-based element design.

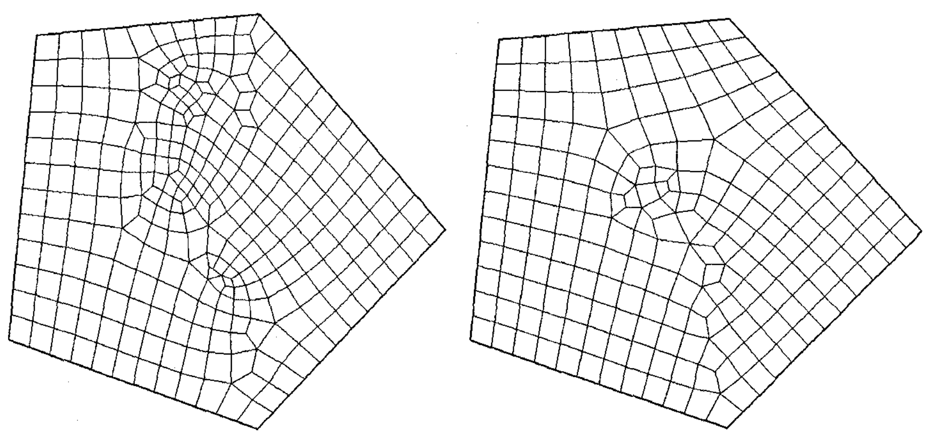
1) Formulating design problem differently

The input of the ANN-based algorithm is the points on the domain boundary. When different number of points is taken as the input for the ANN model, the generated meshes are different. The input points include the reference point and the corresponding leading points. Section 7.4.2 has discussed the influence of the number of the leading points on the generated mesh elements. The comparisons of the mesh results using four leading points and six leading points have been made. Although four leading points have less boundary information, it is easy to include all the patterns in the training samples and so a better mesh can be generated. It can be found that different number of input points changes the formulation of the design problem, and so changes the structure of the ANN-based algorithm.

2) Changing the sequence of environment decomposition

In the finite element mesh design, the element is generated one by one following a sequence. To decide the sequence of decomposing the domain boundary to generate an element is to select the reference point on the boundary. Figure 6-13 has shown two methods of selecting a reference point. The method in Figure 6-13 (a) always chooses the first valid reference point next to the current one from the updated boundary. In another method, the updated boundary will not be processed until all the valid reference points in the original boundary have been processed as shown in Figure 6-13 (b).

Using the two different methods to find reference points for the same domain, different meshes can be generated as shown in Figure 7-20. From the figure, it can be seen that the second method can generate more good-quality elements than the first one. The elements close to the periphery have no obvious difference, but there are more bad elements in the center using the first method. In the first method, the local boundary will become bad with the appearance of a bad element and continue to generate bad elements. However, the second method considers more boundary information by choosing all possible reference points from the original boundary and updates the original boundary with all newly generated elements.



(a) (b)

Figure 7-20 Mesh generation using different methods to find reference point: (a) newer boundary first; (b) older boundary first.

3) Extending synthesis knowledge

To get a different design solution, one important approach is to extend the synthesis knowledge. To extend the synthesis knowledge, the ANN model is employed to train initial training samples and identify the relationship between input and output. The rule-based element extraction method depends on the designers' experience and knowledge. The ANN method does not need to develop basic rules to extract an element from the boundary feature manually. A number of training samples are used to learn the relationship between boundary information and the extracted element. When the boundary becomes complicated or bad elements are generated, the ANN method can continue to generate good-quality elements by adding more patterns into the training samples. Adding more patterns into the algorithm can be also taken as the extending of synthesis knowledge. Therefore, extending synthesis knowledge can be an effective strategy to generate different design solutions, which may lead the possibility of getting creative design.

7.5 Concluding Remarks

The chapter has developed an ANN-based element extraction method for the finite element mesh design problem (Yao et al. 2005). Environment-based design is used to analyze the design problem using environment analysis, conflict identification and concept generation. The cognitive strategies used in ANN-based element extraction method are: changing the number of leading points, the selection of the sequence of environment decomposition based on the older boundary and extending the synthesis knowledge by training the ANN model and adding new patterns to learn the rules automatically. It can be seen that the routes leading to changing design solutions are effective in developing the ANN-based element extraction method.

Chapter 8
Summary and Discussions

8.1 Summary

This research has developed two experimental approaches for understanding conceptual design activities. They are protocol analysis method and virtual experiment. The proposed protocol analysis can be used as the experimental investigation of the contents of the thought process of designers and virtual experiment can be conducted to simulate different design situations and design strategies. Environment-based design is the theoretical background for the experimental investigations.

A protocol analysis experiment was conducted with seven subjects. The subjects were asked to solve a design problem; and after that they were interviewed to recall their design process. The design session and the interview session were recorded, and the recorded data were transcribed, segmented and encoded. Through analyzing the protocol data, an effective protocol analysis method was developed. The protocol analysis method was designed targeting on general design problems; so, it can also be applied in understanding other aspects of design activities and studying human cognitive activities in other domains. The protocol analysis method proposed in this research has also been used to examine some design properties in general design activities and evaluate environment-based design as a descriptive model of design processes.

The environment-based design is a new design methodology. It can theoretically interpret some design properties. On the other hand, the present thesis took the observed design properties as hypotheses and designed a virtual experiment to demonstrate and examine the hypotheses based on a finite element mesh design problem. The results have shown that the hypotheses are validated through the virtual experiment. These hypotheses provide alternatives for increasing the chances of getting creative design solutions by providing three routes for changing design solutions. Finally, the three routes are applied on the mesh generation design problem as cognitive strategies for developing an effective ANN-based element extraction method.

8.2 Recommendations to Support Product Design and Development

This present research has provided an experimental framework for understanding design activities. From the research results for investigating design activities, a few recommendations for supporting product design and development are summarized as below.

1) An effective protocol analysis method has been developed to understand designers' cognitive processes and activities. This protocol analysis method is designed based on the requirements analysis of designing protocol experiments, which includes defining the experimental objective, experiment set-up, transcription, segmentation, encoding as well as data analysis. This experiment is designed to completely and accurately record designer's cognitive activities and behaviors while minimize the interference to the designers during the design process. The protocol analysis method proposed in this research can be applied to

analyze other protocol data in design research and study the human cognitive activities in other domains.

2) From the comparisons of two subjects' design concepts using protocol analysis, it can be suggested that a designer recognize all related environment components and figure out their relationships between environment components in order to deliver a good concept.

3) EBD is a prescriptive design methodology, which can guide designers from the gathering of customer requirements throughout the generation and evaluation of design concepts. The results of protocol analysis has been also been taken as a cognitive experiment to examine whether EBD is a descriptive model. The cognitive experiment has been used to examine the process flow of EBD and the four main theorems behind the EBD methodology. The cognitive experiment shows that the EBD methodology reflects the nature and the characteristics of the design process. So EBD can be also used as a descriptive model of the natural design process that illustrates how designers conduct a design task. EBD can be taken as the descriptive model for further studying designer's cognitive activities.

4) This present research observed three routes leading to the changes of design solutions. They are: formulating design problems differently, changing the sequence of decomposition of design problems and extending synthesis knowledge. The three routes have been theoretically explained by EBD theory. A virtual experiment is designed to validate three routes based on a finite element

mesh design problem. The results have shown that the hypotheses are validated through the virtual experiment. So the three routes provided alternatives for changing design solutions. As well known, the most creative aspect of design is the development of new design ideas, the three routes can be used as cognitive strategies for designers to increase the chances of getting creative design solutions.

Chapter 9
Conclusions and Future Work

9.1 Conclusions

The goal of this research is to find effective and feasible experimental approaches to study designers' cognitive activities and understand design properties. For the purpose of this study, a product-environment-based protocol analysis method is developed to study designers' cognitive activities and a virtual experiment is conducted to simulate different design properties.

In this protocol analysis experiment, designer's activities were recorded when solving a design problem and designers were asked to recall their design process right after finishing the design. Then, the recorded verbal data are analyzed by transcribing, segmentation and encoding for further analysis. In general, protocol analysis is to transform the unstructured data collected from designers into structured data. Existing protocol analysis methods to study designers' cognitive activities are developed based on specific design problems, specific domains and the persons who analyze the protocol data. The new protocol analysis method is developed based on the concept of design states and recursive object model, which reflect the nature and characteristics of a design process. It can be easily applied to any design problem and any domain. This method can quantify the changes of designers' cognitive activities during a design process. Some guidelines and recommendations for assisting designers to deliver an innovative design are summarized based on the experimental results.

Another part of this research is to simulate and examine design activities using a virtual experiment. In the virtual experiment, the selected finite element mesh design problem can be automatically solved under a program developed in the computer environment based on a rule-based element extraction method. Then, different settings of the parameters, different strategies, and different formulation of design requirements and different sequence of solving the problem are simulated to compare their influences on the results. Three routes leading designers to generating different design solutions are proposed and examined through this virtual experiment. The three routes leading to different designs have been applied to develop a new artificial neural network-based element extraction method for the finite element mesh design problem. Numerical experiments on quadrilateral mesh generation have shown that this method is effective.

9.2 Future work

In this present thesis, a new protocol analysis method is proposed and a virtual experiment to simulate different design activities is conducted. The results have shown they are effective and feasible to understand design activities. The following work can be continued in the future.

1) This thesis has proposed an effective verbal protocol analysis method for studying designers' cognitive activities. This method has examined some design properties and got some observations from the protocol data. The protocol data can be

further analyzed to quantify designers' mental stress and examine other design properties.

2) The verbal protocol analysis method can be combined with other human measurements, such as eyegaze tracking equipment, EEG system, etc. to further understand how design creativity is generated. A cognitive model of understanding designers' cognitive activities can be developed based on the analysis of the experimental data.

3) The computerized simulation model developed in the virtual experiment can be used to examine other design phenomena and verify other existing design theories.

4) The observations from the experimental studies can be used to guide the development of a software prototype to assist designers in generating innovative design solutions.

5) The ANN-based element extraction method can be improved by using a better learning algorithm and can be extended to 3D domain mesh generation.

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Appendix 1

CONSENT FORM TO PARTICIPATE IN RESEARCH

This is to state that I agree to participate in a program of research being conducted by Dr. Yong Zeng of Concordia Institute for Information Systems Engineering of Concordia University.

A. PURPOSE

I have been informed that the purpose of the research is to develop a designer's cognitive model and a software prototype to implement the model for assisting designers to make important decisions leading to innovative product design.

B. PROCEDURES

This research will be conducted in the design lab, located in EV10.177 at Concordia University.
I understand that my participation will require me to:

1) Work on a design problem that involves no intellectual property of any party;
2) Complete the design problem in the regular business way. During this process, I will be asked to verbally describe what I am doing and my thought process.
3) Answer questions regarding the design from researchers of Concordia University.

C. CONDITIONS OF PARTICIPATION

- I understand that I am free to withdraw my consent and discontinue my participation at anytime without negative consequences.
- I consent to be video- and audio- taped as I work on my design problem. Yes ☐ No ☐
- I understand that the data from this study may be published.
- I understand that my participation in this study is CONFIDENTIAL, that is, the researcher will know but will not disclose my identity, and that my name will not appear in any published data.

I HAVE CAREFULLY STUDIED THE ABOVE AND UNDERSTAND THIS AGREEMENT. I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

NAME (please print) ____

SIGNATURE ____

WITNESS SIGNATURE ____

DATE ____

If at any time you have questions about your rights as a research participant, please contact Adela Reid, Research Ethics and Compliance Officer, Concordia University, at (514) 848-7481 or by email at areid@alcor.concordia.ca.

Appendix 2

SURVEY FORM TO PARTICIPATE IN RESEARCH

In order to better analyze the data from the experiments, we need to know the background of the subjects. A subject will be issued with a subject number. The name of the subjects will never be used in the presentation or publication of the results unless you specifically are asked and consent to such a use. Any information related with this research we get from you is confidential.

Subject No. ____________________

Date: ___________________________

Name (please print) _________________________

Signature: __________________________

Sex: _________

Age: _________

Degree: ___________________

Major: ___________________

Questions:

1. Have you designed something before? If yes, what did you design?

2. Have you studied any design theory or methodology? If so, what did you learn before?

3. Do you have any work experience in design, mechanical, electrical, or civil? If so, how many years have you designed and what is your related experience briefly?

If at any time you have questions about your rights as a research participant, please contact Adela Reid, Research Ethics and Compliance Officer, Concordia University, at (514) 848-7481 or by email at areid@alcor.concordia.ca.

Appendix 3

Complete transcript of subject 1

"First, I got your design problem. The first point of the design problem is that I want to make clear what the thing to be designed is. We made clear that we need to design a garbage bin. Then I think what the environment for this garbage bin is. In which place should it be put? Like this coach car or sleeping car? Then I consider the structure of the coach car. Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table. It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats, tables (point to the sketches on the screen). This place (under the seats) is not convenient for picking up. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle. That is close to the aisle. How to put there? I am thinking how it is positioned. Is it an ordinary garbage bin? Where should it be put? You have to think how to arrange it if you use a device for automatic collection. If I follow a simple garbage bin…. I just draw a garbage bin very simply. I think the garbage bin is put here, then whether the cover should be open from the front or from the side, and whether the garbage cart should come under the garbage bin and whether it is convenient to take out the garbage bag. If it is a bucket, then I think about the bag because you cannot put the garbage into the bin directly. Otherwise the bin is too dirty. If you use a bag, which direction should the bag be open? Should the bucket be put on the side of the seats? If it is on the side, then …. Now I draw another view, from the side of the chair. The bin cannot be put exactly along the side of the chair. Otherwise your feet cannot move conveniently and probably the dirt from the surface of the bin can make your pants dirty. So I think about the position of this direction, the chair, the ground, probably go inside a little bit… Approximately garbage bin is put at this position. When I draw this position, I begin to think. First, we have to consider how you put the garbage? If you open like this way, and put garbage in, then for people sitting beside you to put garbage, you have to move your position to let him put. If you put this way, to open it will affect people sitting beside you, and then you have to consider how the cleaners come to pick up the garbage. If cleaners pull the garbage out directly, it looks disgusting, very dirty, because it is too close to people. Here I still think how to put the plastic bag in the garbage bin. I think about the plastic bag we often use, take the bag out, bind it and then put in the middle. The process is too long. Cleaners open the cover of the garbage bin, and (take out), and then put another new bag, then you …, considering garbage is too close to passenger, I think the time should be short as soon as possible. My personal feeling is I deal with the garbage bag… Here I think whether the garbage bag can be automatically packed, and how to make it. I draw and think whether I can figure out a device, then … Finally this scheme is rejected. So it is not good to put aside or inside, especially not good in every blocks since you have to install a lot of garbage bins (in every blocks), not good. I think this strategy is not suitable. Therefore at this moment, I decide to reject this scheme and go back to the beginning. So

I go back to the beginning, I think to analyze the environments again. Excluding these previous strategies, which position is better, then … If you install here, at every seat, because it is not good for the four persons use one garbage bin, yes, and no one would like to sit close to the garbage bin … then I think, in the train, what are the contents of the garbage? The garbage in the train is generally peel, paper, etc. The major things are peel, not big things. Things are small. Then I think to put a big garbage bin, and cleaners go directly to pick them up, but not conveniently so I cancelled. There is a big space close to the window, but now I think again the garbage is small, so I can completely make a simple stuff, something like a conveyor belt, under the window. Since the wall of the compartment is quite thick, the interior of the wall of the compartment need to keep temperature, keep warm, there is space inside the wall. We can make this (conveyor belt) in the wall of the compartment. Then I returned to the wall I draw, then I spread out the idea, how to design plastic bag. Details will be used later. Now you see, this is the side wall of the compartment. This is table, beside which are chairs (pause). The green line (which is the garbage channel) is very narrow. The narrow space is enough for you. I need to consider the thickness of the wall of the compartment and the space of the wall cannot be occupied completely. Finally the garbage bin can be hidden inside the wall and you cannot see the garbage bin. There is only a small stainless window. By pushing the window, you can deposit the garbage. Now I start to design this system. After the system is designed, you can divide it into small pieces. That is detail design. Now I suddenly got an idea. If the garbage passes in the channel, how to pack the garbage? I cannot let the garbage pass on the belt directly. How to design? I suddenly think about the plastic zipper on the plastic bag. You see one side is like this, under that is like a small ball. The two parts touch and then they are attached. Now it works like this way. I let the bag open when it passes this position (where passenger sits). Here there is a kind of device to make it open. After it is open, it can be closed. The garbage can be deposited at the open place of the plastic bag. Now there is an idea. If I let it open at this position, the garbage is deposited here. When the belt continues to move, the opened bag will be closed. So the garbage bag will be designed very long, along this direction. When it passes passengers, it will open. Otherwise it is locked. Here is the window. By pushing the window, passengers can deposit the garbage. This process can be time-set. Setting 10 minutes, it passes one section, then it is open. I cannot transfer the garbage of one passenger to the place of another passenger. Otherwise it is not good to another passenger to open to see other people's garbage. So I think to set the garbage bag one section by one section. This is a table. The conveyor belt passed the table. When the conveyor belt passed the whole compartment, we will change a new garbage bag and collect the garbage. Then I consider, if I install one garbage window for every seat. But I consider installing it symmetrically, which is good for the whole programming design. So finally one table corresponds to one garbage window. This is table. This is garbage window. In this way, all passengers around the table can deposit garbage conveniently by pushing the garbage window. Then the garbage bin system for the whole compartment can be accessed by passengers symmetrically. Then I want to talk about the windows of the garbage bin system. Then I think how to transfer the garbage. I write, "every 10 minutes, move once". It doesn't matter for the time. The key point is that garbage bag, for passengers, can be transferred to this position and stop. So I assume now it is empty. Then it goes, 10 minutes, one block, then it is opened, you can deposit things. After another 10 minutes, it goes to another block automatically. Then stop here for passengers to deposit garbage. Then go another 10 minutes. After the 30 minutes, here is a kind of device to collect garbage at the end of the compartment. The garbage of the whole compartment will be collected. The 30 minutes are decided by the number of passengers. You can use simple one-chip machine to control it. You can use other automatic way to control it. Now I think about the relations between garbage bag and the channel. This is the wall, and then it is the channel where garbage moves. This is the cross-section view of the garbage bag. The cross-section view is how we seal the bag. I didn't make the seal on the top of the bag, but in the middle. There are two round sticks on the top. When the bag moves, the round sticks are locked so that it will not fall down. Then outside of the bag is the channel. The channel cannot move. It is metallic and other material, which are fixed with the wall. When the bag is full and the top of the bag is sealed, it moves in the channel. But the top of the bag should not have friction. Otherwise it could be broken. You also cannot make it hang in the air and it also could be broken. So I simply design a conveyor belt at the bottom of the channel. Under the belt, the rollers are added. We cannot make the bag touch with the roller directly because the bag is the simple one, low cost. This is the belt, roller. There is no relative movement between them, then the garbage is transmitted in this way. Now what you see is the detail structure of the garbage bag. The main concepts are in the two graphs. Now I consider the plastic bag, namely garbage bag for the whole compartment. I need to consider how to put the garbage bag and how to collect the garbage bag, then how is the process of the bag moving? When the bag is done, it is just one bag. It is rolled like the paper rolls from the manufacturer. When it is installed from one side of the compartment, it will fill the whole channel of the compartment with the moving of the conveyor belt. The bag should be longer than the length of the compartment. The bag stops, it can be open with a zipper for the passenger to deposit garbage. When it is moving, it is closed. So the garbage bag stops and moves for several blocks until it is filled. Then we will collect the whole garbage bag from the other end of the compartment. Then we will change a new bag in the channel. "

Final segment and encoding for subject 1

1) First, I got your design problem. The first point of the design problem is that I want to make clear what the thing to be designed is. We made clear that we need to design a garbage bin.
S1=a garbage bin
E1= Φ
B1= Φ

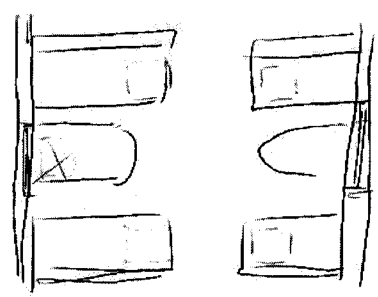
2) Then I think what the environment for this garbage bin is. In which place should it be put? Like this coach car or sleeping car? Then I consider the structure of the coach car.

e1=coach car, location of the garbage bin, e2=S1=garbage bin
s2= Φ, S2=s2∪S1=garbage bin
B2= considering the structure of the coach car when a garbage bin is put there

3) Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table.
e1=cleaner, e2=table, e3=aisle, e4= S2=garbage bin
s3=the location of the garbage bin: to put the garbage bin under the table
b1=how cleaners can pick up the garbage bin conveniently;
b2=cleaners walk along the aisle;
b3=garbage bin is put under the table.

4) It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats, tables (point to the sketches on the screen).
e1=passenger, e2=seats, e3=table, e4=S3
s4=the location of the garbage bin: to put the garbage bin under the seats
b1=the location of putting garbage bin under the table affects the movement of passenger's legs;
b2=the only place is under the seats considering seats, tables.

5) This place (right under the seats) is not convenient for picking up by cleaners. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle.



e1=cleaners, e2=seats, e3=aisle, e4=S4
s5=the location of the garbage bin: to put the garbage bin along the side of the seats close to the aisle
b1=the location of putting under seats is not convenient for cleaners to pick up;
b2=considering putting the garbage bin along the side of seats close to the aisle.

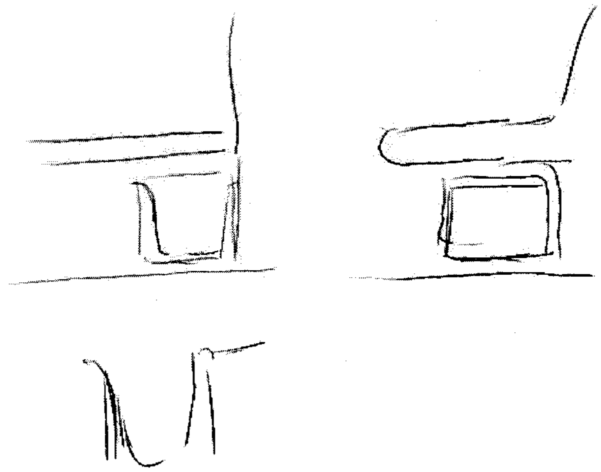
6) That is close to the aisle. How to put there? I am thinking how it is positioned. Is it an ordinary garbage bin? Where should it be put? You have to think how to arrange it if you use a device for automatic collection. If I follow a simple garbage bin.... I just draw a garbage bin very simply. I think the garbage bin is put here.

e1=aisle, e2=device for automatic collection, e3=S5
s6=a simple garbage bin
b1=how the garbage bin is positioned, close to the aisle;
b2=how to arrange it if using device for automatic collection.

7) Then whether the cover should be open from the front or from the side, and whether the garbage cart should come to the garbage bin and whether it is convenient to take out the garbage bag.
e1=S6, e2=garbage cart, e3=garbage bag, e4=cover, e5=cleaner
s7= Φ
b1=considering the cover of the garbage bin should be open from the front or from the side;
b2=considering how the garbage cart comes to the garbage bin;
b3=considering how the cleaner can take out the garbage bag conveniently.

8) If it is a bin, then I think about the bag because you cannot put the garbage into the bin directly. Otherwise the bin is too dirty. If you use a bag, which direction should the bag be open? Should the bin be put on the side of the seats? If it is on the side, then ....
e1=garbage bag, e2=garbage, e3=S7, e4=passenger, e5=seats
s8=garbage bag is used for passengers to put garbage into the bin
b1=considering which direction the garbage bag should be open;
b2=passengers cannot put the garbage into the bin directly;
b3=considering whether the bin should be put on the side of the seats.

9) Now I draw another view, from the side of the seats. The bin cannot be put exactly along the side of the seat. Otherwise your feet cannot move conveniently and probably the dirt from the surface of the bin can make your pants dirty. So I think about the position of this direction, the seat, the ground, probably (the garbage bin) go inside a little bit... Approximately garbage bin is put at this position (go inside of the seats a little bit, under the seats close to the aisle).



e1=seats, e2=S8, e3=passengers, e4=garbage, e5=ground
s9=the location of the simple garbage bin: to put inside seats a little bit, under the seats close to the aisle.
b1=the bin cannot be put exactly along the side of the seats since the feet of passengers cannot move conveniently and the dirt from the surface of the bin can make the pants of the passengers dirty;
b2=considering the seat, the ground, the garbage bin go inside the seats a little bit.

10) When I draw this position (under the seat close to the aisle), I begin to think. First, we have to consider how you deposit the garbage? You pull and open the garbage bin, and then deposit garbage. But for people sitting beside you to deposit garbage, you have to move your position to let him/her deposit garbage.
e1=passenger, e2=garbage, e3=S9
S10=S9
b1=considering how passengers deposit the garbage into the bin;
b2=passengers open the garbage bin, and then deposit garbage;
b3=passengers have to move their body to let other passengers sitting beside them deposit garbage

11) Then you have to consider how the cleaners come to pick up the garbage. If cleaners pull the garbage out directly, it looks disgusting, very dirty, because it is too close to people.
e1=cleaners, e2=garbage, e3=S10, e4=passengers
b1=considering how cleaners pick up the garbage;
b2=the garbage makes people disgusting when cleaners pull the garbage out directly

12) Here I still think how to put the plastic bag in the garbage bin. I think about the plastic bag we often use, take the bag out, bind it and then put in the middle. The process is too long. Cleaners open the cover of the garbage bin, and (take out), and then put another new bag, then you ….

e1=plastic bag, e2=cleaners, e3=S11
b1=thinking how to put the plastic bag in the garbage bin;
b2=considering the process how cleaners take out garbage bag, bind it, put another new bag…

13) Considering garbage is too close to passenger, I think the time should be as short as possible. My personal feeling is I deal with the garbage bag… Here I think whether the garbage bag can be automatically packed, and how to make it.
e1=garbage, e2=passengers, e3=garbage bag, e4=cleaners, e5=S12
b1=considering the time of collecting garbage for cleaners should be as short as possible since the garbage is too close to passengers;
b2=considering whether the garbage bag can be automatically packed, and how to make it.

14) Finally this scheme is rejected. So it is not good to put aside or inside, especially not good in every blocks since you have to install a lot of garbage bins (in every blocks), not good. I think this strategy is not suitable. Therefore at this moment, I decide to reject this scheme and go back to the beginning.
e1=the scheme of the location of the garbage bin, e2=train, e3=compartment
s14= Φ
b1=considering the installation of garbage bins in every compartment of the train, the scheme is rejected.

15) I draw and think whether I can figure out a device, then … So I go back to the beginning, I think to analyze the environments again.
Meta-language

16) Excluding these previous strategies, which position is better, then … If you install here (under the table), at every seat, because it is not good for the four persons use one garbage bin, yes, and no one would like to sit close to the garbage bin …
e1=table, e2=seat, e3=passengers, e4=garbage, e5=S14
b1=no passenger likes to sit close to the garbage bin
b2=considering a better location of garbage bin

17) Then I think, in the train, what are the contents of the garbage? The garbage in the train is generally peel, paper, etc. The major things are peel, not big things. Things are small. Then I think to put a big garbage bin in one compartment, and cleaners go directly to the garbage bin and pick them up.
e1=train, e2=passengers, e3=garbage, e4=cleaners, e5=S16
s17=a big garbage bin in one compartment
b1=considering the contents of garbage in the train are small things;
b2=cleaners go directly to the garbage bin.

18) The previous strategy is not convenient for passengers.

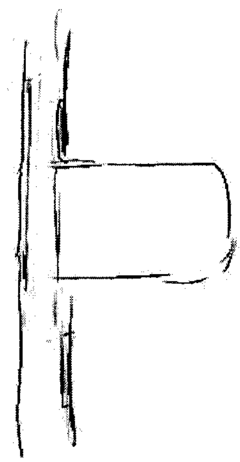
e1=passengers, e2=garbage, e3=S17
b1=the big garbage bin is not convenient for passengers.

19) There is a big space close to the window. I think again the garbage is small, so I can completely make a simple stuff, something like a conveyor belt, under the window.
e1=window of the compartment, e2=wall of the compartment, e3=garbage, e4=S18
s19=a conveyor belt
b1=there is a big space close to the window;
b2=the garbage is small
b3=considering to make a simple stuff under the window in the wall

20) Since the wall of the compartment is quite thick, the interior of the wall of the compartment need to keep temperature, keep warm, there is space inside the wall. Now you see, this is the wall of the compartment. We can make this (conveyor belt) inside the wall of the compartment.
e1=table, e2=compartment, e3=S19
s20=a conveyor belt inside the wall
b1=there is space inside the wall;
b2=considering to make the conveyor belt inside the wall

21) This is table, beside which are seats (pause). The green line (which is the garbage channel) is very narrow. The narrow space is enough for you (passengers). I need to consider the thickness of the wall of the compartment and the space of the wall cannot be occupied completely.
e1=table, e2=seats, e3=compartment, e4=passengers, e5=wall, e6=garbage, e7=S20
s21=a garbage channel for conveyor belt system
b1=the space of the garbage channel is enough for passengers;
b2=considering the thickness of the wall of the compartment and the space of the wall

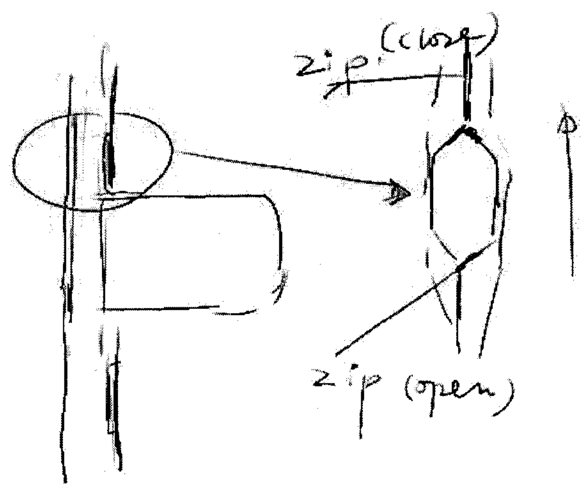
22) Finally the conveyor belt system can be hidden inside the wall and you cannot see the system from outside. There is only a small stainless window (on the wall of the compartment). By pushing the window, you can deposit the garbage.



e1=wall, e2=S21, e3=passengers, e4=garbage
s22=a small stainless window on the wall of the compartment for garbage deposit
b1=considering how to deposit garbage to the conveyor belt system;
b2=considering to deposit garbage by pushing the stainless window.

23) Now I start to design this system. After the system is designed, you can divide it into small pieces. That is detail design.
Meta-language

24) Now I suddenly got an idea. When the garbage passes through the channel, how to pack the garbage? I cannot let the garbage pass on the belt directly. How to design? I suddenly think about the plastic zipper on the plastic bag. You see one side is the tape on the top of the plastic bag, under that is a slider, like a small round stick. The two parts touch and then they are attached. Now it works like this way.



e1=garbage, e2=garbage channel, e3=S22
s24=a plastic zipper on the plastic bag is used to pack garbage in the channel

b1=considering to pack the garbage passing through the garbage channel

25) I let the bag open when it passes by this position (where passenger sits). Here there is a kind of device to make it open. After it is open, it can be closed. The garbage can be deposited at the open place of the plastic bag.
e1=passengers, e2=garbage, e3=S24, e4=garbage bag
s25=a kind of device to make the garbage bag open
b1=considering the garbage can be deposited when the bag is open to pass passengers

26) Now there is an idea. If I let it open at this position, the garbage can be deposited here. When the belt continues to move, the opened bag will be closed. So the garbage bag will be designed very long, along the garbage channel. When it passes by passengers, it will become open. Otherwise it is locked.
e1=garbage bag, e2=garbage, e3=belt, e4=channel, e5=passengers, e6=passengers, e7=S25
s26=a garbage bag is designed very long along the garbage channel
b1=garbage can be deposited when the bag is open;
b2=considering the bag will be closed when the belt continues to move and the bag will be opened when it passes passengers;
b3=considering the bag is long, along the garbage channel

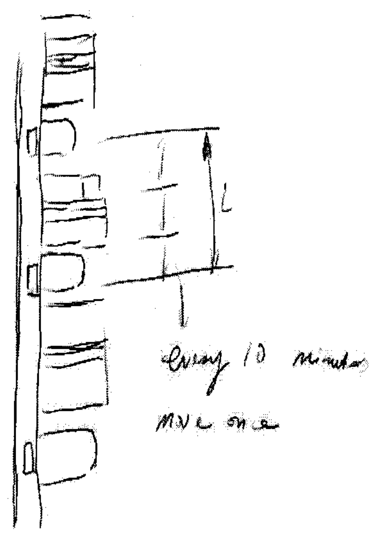
27) Then I consider whether I should install one garbage window for every seat. But I consider installing it symmetrically, which is good for the whole programming design. So finally there is one garbage window corresponding to one table. This is table. This is garbage window. In this way, all passengers around the table can deposit garbage conveniently by pushing the garbage window. Then the litter-disposal system for the whole compartment can be accessed by passengers symmetrically.
e1=garbage window, e2=seat, e3=table, e4=compartment, e5=S26, e6=passengers, e7=garbage
s27=the installation of garbage window symmetrically corresponding to a table
b1=considering to install one garbage window for every seat;
b2=considering to install the garbage windows symmetrically corresponding to the tables;
b3=considering the convenience for all passengers around the table to deposit garbage

28) Then I think how to transfer the garbage. Here is the garbage window. By pushing the window, passengers can deposit the garbage. This process can be time-set. I write, "every 10 minutes, move once". It doesn't matter for the interval time. The key point is that garbage bag, for passengers, can be transferred to this position (where passengers sit) and stop. Setting 10 minutes, it passes by one section, and then it becomes open and you can deposit things. After another 10 minutes, it goes to another block automatically.
e1=garbage, e2=garbage window, e3=passengers, e4=S27
s28=time set for opening the garbage bag to deposit garbage
b1=considering how to transfer the garbage;

b2=considering to make the time-set for passengers to deposit garbage

29) I cannot transfer the garbage at the place of one passenger to the place of another passenger. Otherwise it is not good for another passenger to open to see other people's garbage. So I think to let the garbage bag move one section by one section. This is a table. The conveyor belt passed the table.
e1=passengers, e2=garbage, e3=garbage bag
s29=the transferring of the garbage is make by moving the garbage bag one section by one section between tables
b1=passengers don't like to open garbage bag to see garbage transferred from other passenger's place

30) When the conveyor belt passed the whole compartment, we will change a new garbage bag and collect the garbage. After let's say 30 minutes, here is a kind of device to collect garbage at the end of the compartment. The garbage of the whole compartment will be collected. The 30 minutes are decided by the number of passengers. You can use simple one-chip machine to control it. You can use other automatic way to control it.



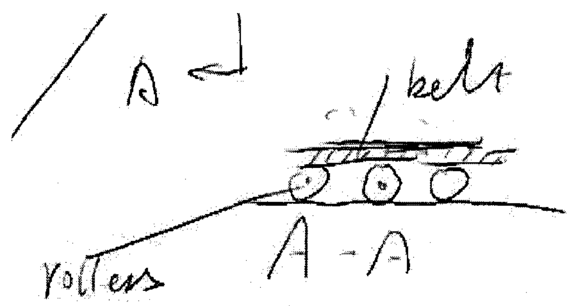
e1=belt, e2=compartment, e3=garbage bag, e4=passengers, e5=cleaners, e6=garbage
s30=the collection of garbage at the end of the compartment after a set of time
b1=considering the belt passing the whole compartment;
b2=considering the cleaners change the garbage bag;
b3=considering the time set for changing the a garbage bag is decided by the number of passengers.

31) Now I think about the relations between garbage bag and the channel. This is the wall, and then it is the channel where garbage moves. This is the cross-section view of the garbage bag. The cross-section view is how we seal the bag. I didn't make the seal on the top of the bag, but in the middle. There are two round sticks on the top. When the bag moves, the round sticks are locked so that it will not fall down.

e1=garbage bag, e2=garbage channel, e3=S30
s31=two round sticks used to lock the middle of the bag with the top
b1=considering garbage moving in the channel

32) Then outside of the bag is the channel. The channel cannot move. It is metallic and other material, which are fixed with the wall.
e1=garbage channel, e2=wall, e3=S31
s32=the material of the garbage channel: metallic or other material
b1=considering the channel cannot move and it is fixed with the wall

33) When the bag is full and the top of the bag is sealed, it moves in the channel. But the top of the bag should not have friction. Otherwise it could be broken. You also cannot make it hang in the air and it also could be broken. So I simply design a conveyor belt at the bottom of the channel. Under the belt, the rollers are added. We cannot make the bag touch with the roller directly because the bag is the simple one, low cost. This is the belt, roller. There is no relative movement between them, and then the garbage is transmitted in this way.



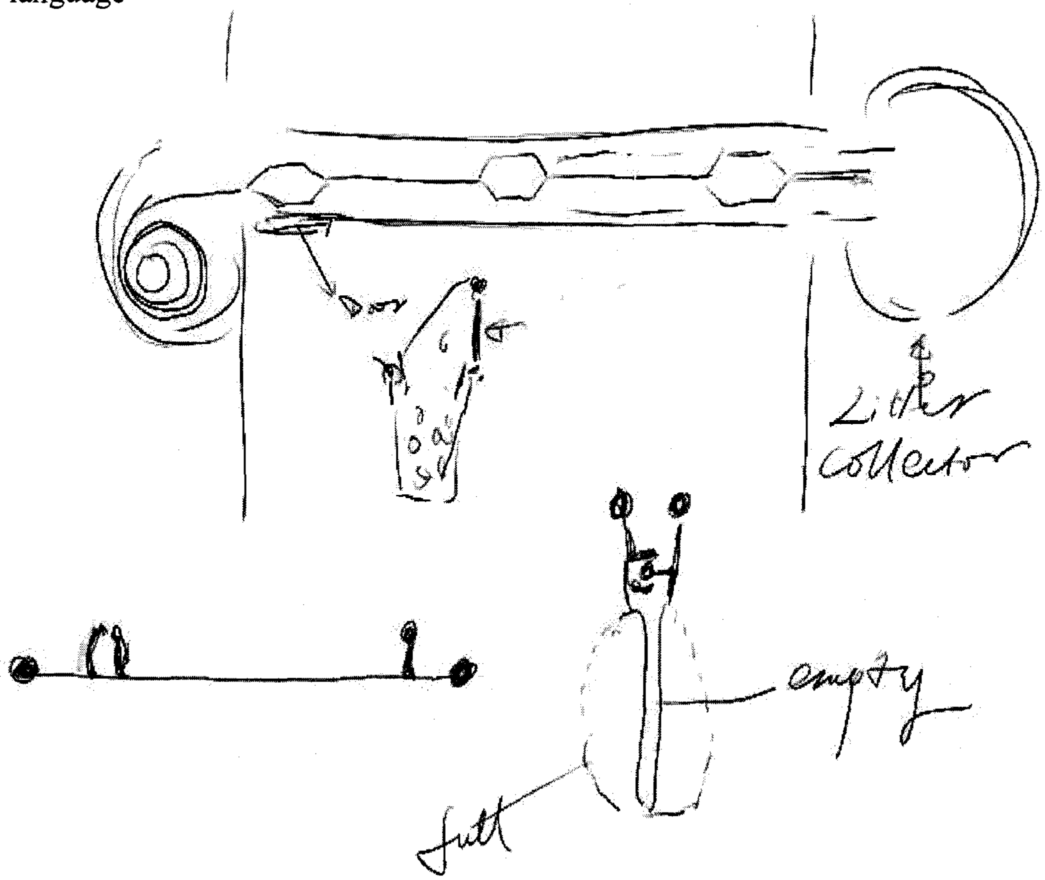
e1=garbage bag, e2=channel, e3=belt, e4=S32
s33=rollers added under belt
b1=considering the garbage bag should not have friction with the channel;
b2=considering the garbage bag cannot touch with the roller directly

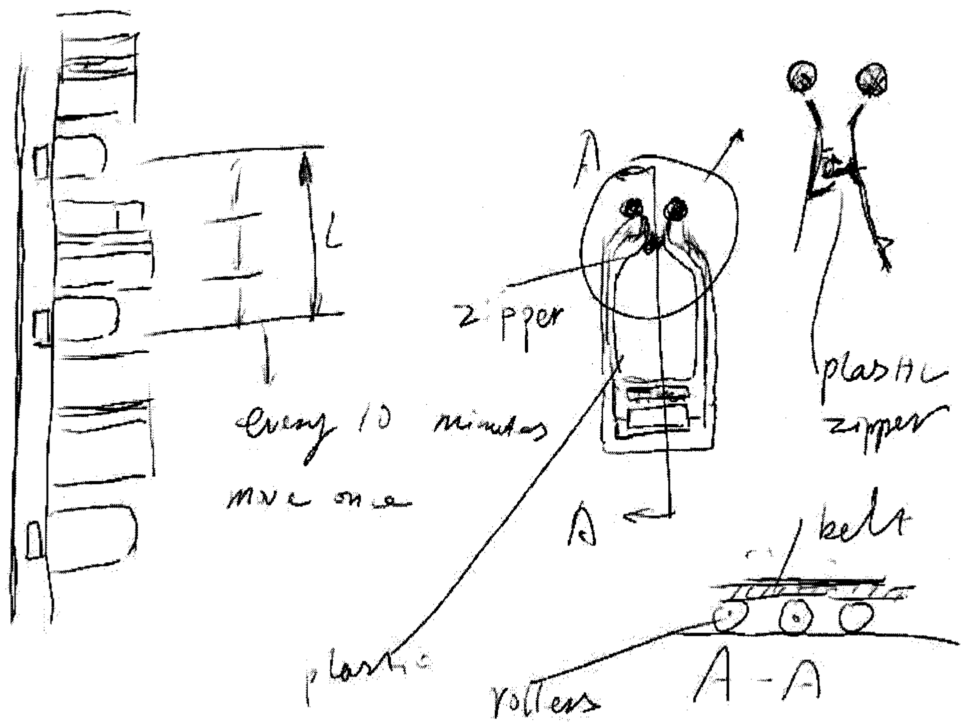
34) Now what you see is the detail structure of the garbage bag. The main concepts are in the two graphs.
Meta-language
35) Now I consider the plastic bag, namely garbage bag for the whole compartment. I need to consider how to put the garbage bag and how to collect the garbage bag, then how is the process of the bag moving? When the bag is done, it is just one bag. It is rolled like the paper rolls from the manufacturer. When it is installed from one side of the compartment, it will fill the whole channel of the compartment with the moving of the conveyor belt. The bag should be longer than the length of the compartment.
e1=plastic bag, e2=compartment, e3=cleaners, e4=S33, e5=manufacturer, e6=belt
s35=one bag rolled and installed from one side of the compartment and collected at the other side

b1=considering how to put the garbage bag in the system;
b2=considering how to collect the garbage bag;
b3=considering how the process of the bag moving;
b4=considering the plastic bag rolls from the manufactuer;
b5=considering the bag should be longer than the compartment

36) The bag stops, it can be open with a zipper for the passenger to deposit garbage. When it is moving, it is closed. So the garbage bag stops and moves for several blocks until it is filled.
Meta-language

37) Then we will collect the whole garbage bag from the other end of the compartment. Then we will change a new bag in the channel.
Meta-language





L
every 10 minutes
move once
A
zipper
A
plastic
plastic
zipper
belt
rollers
A - A