Knowledge-based collaborative decision making in product design

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Knowledge-based Collaborative Decision Making in Product Design

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School of Mechanical and Aerospace Engineering

A thesis submitted to the Nanyang Technological University in
fulfilment of the requirement for the degree of

Doctor of Philosophy

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ABSTRACT

In the global dynamic market, the design of new products is increasingly a focal point of competition. Team collaboration and decision making play essential roles in product design, and sharing of knowledge is critical to facilitate decision making. Most environments for team collaboration and decision making in product design are aided by technologies, such as knowledge-based systems.

However, many existing knowledge-based systems are poorly integrated with the design process. It is essential to understand how people use knowledge to make decisions. This research aims to understand how knowledge is used in various design activities from a human factors perspective, and develop a methodology that can be used to support collaborative decision making in product design. The research explored how teams collaborate in knowledge sharing and facilitated knowledge utilization for decision making. By studying design behavior this research tries to understand knowledge sharing and utilization in product design.

Based on the literature review, surveys and interviews, important factors for the support of collaborative decision making in product design were identified. A knowledge-based collaborative decision making model was developed. Knowledge in product design was identified and the knowledge processing was described. A knowledge modeling method was developed for knowledge-based collaborative decision making support. Experimental studies were undertaken to explore the understanding of knowledge, activities and design space. Five groups of four experienced designers were observed as they designed artifacts. During these sessions of designing artifacts the group dynamic behavior was observed for conceptual design, system level design and detail design.

The results provide the understanding of the content, action and context of knowledge in product design. The results also provide the answers to what knowledge is used, how the knowledge is communicated, and how the knowledge is integrated into design space in different design phases. The theoretical implications for future research and practical implications were presented. This research may improve the integration of human and knowledge-based systems. It will provide rich insight for research in knowledge management, team collaboration and decision making in product design.

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Chapter 1 Introduction

1.1 Background

Good product design and product innovation are important to gain a competitive advantage (Ulrich & Eppinger, 2004). Companies must develop innovation capabilities across all stages of the product design process (Ulrich & Eppinger, 2004). The capabilities for continuous product innovation are associated with a company's knowledge management systems (Ronchi, Chapman, & Corso, 2003), team collaboration mechanism (Moenaert, Caeldries, Lievens, & Wauters, 2000) and decision making strategy (Powell & Buede, 2006; Schmidt, Montoya-Weiss, & Massey, 2001). Companies must therefore strive to continuously improve these capabilities.

Successful product design relies on knowledge management, and failure to share and exploit knowledge often prevents companies from developing innovative ideas (Nonaka & Takeuchi, 1995). Therefore understanding the knowledge in design is increasingly important to maintain competitive advantage (Seely-Brown & Duguid, 2000). New knowledge is required to create an ongoing stream of new products and methods, and to grow an organization's capabilities (Leonard-Barton, 1995; Nonaka & Takeuchi, 1995). To increase a company's ability to derive competitive value from knowledge requires an understanding of the organization's work system and organizational design, therefore affects a company's ability to acquire, create, and apply knowledge (Mohrman, Finegold, & Mohrman, 2003).

Product design is typically executed in a design team (Van Engelen, Kiewiet, & Terlouw, 2001). Knowledge needs to be accessed efficiently by the design teams (Ahmed, 2005). It is important to speed up the product design process, particularly when it concerns collaboration with others (May & Carter, 2001). Nonaka & Takeuchi (1995) suggested encouraging knowledge sharing and fostering a learning culture that improve individuals as well as teams. Knowledge is shared through team collaboration and utilized for decision making in design. Decision-making is a

knowledge-intensive activity, and proficiency in knowledge management is hence increasingly important to improve product design (Holsapple, 2001).

To enable an efficient and timely product design, companies must spread knowledge across various functional departments and individual employees, (Mohrman, Finegold, & Mohrman, 2003). Many tools and techniques have been utilized in an attempt to make the design process more effective. Unfortunately, product design is still prone to failure (Cooper, 2003). Most companies have yet to master the ability to consistently bring products to the market at the right time, at the right price, and with the right customer needs fulfilled (Mohrman, Finegold, & Mohrman, 2003). The use of a cross-functional team does not guarantee effective design; the teams also need to be tightly integrated and strongly coordinated (Jassawalla & Sashittal, 1998). The absence of a proper decision strategy for cross-functional teams can lead to poor designs and/or unnecessary iterations (Smith & Eppinger, 1997). Leveraging on collaboration across various departments to enable an efficient and timely decision making remains a constant challenge for organizations (Holsapple, 2001).

This research aims at identifying the knowledge needed in design, analyze the activities such as knowledge management, team collaboration and decision making, which are involved in sharing and utilizing design knowledge, and explore the understanding of design process. This research aims at understanding the designers so as to leverage on information and communication technology (ICT) support for their knowledge-based collaborative decision making in design.

1.2 Motivation

The product design process is complex and involves the management of knowledge (Ronchi, Chapman, & Corso, 2003), team collaboration (Moenaert, Caeldries, Lievens, & Wauters, 2000), decision making (Powell & Buede, 2006; Schmidt, Montoya-Weiss, & Massey, 2001) and ICT support (Majchrzak, Rice, Malhotra, King, & Ba, 2000; Ullman, 2002), see Figure 1-1.

Figure 1–1 Knowledge and activities involved in product design

As illustrated in Figure 1-1, ICT supports knowledge management, team collaboration and decision making in product design. Knowledge is the source of innovation in product design. It may be shared through team collaboration and utilized for decision making. Product innovation may be slow. Understanding and promoting the knowledge in product design is important to product innovation (Ronchi, Chapman, & Corso, 2003). Despite the onward march of technology in these years, a fundamental understanding of design activity is still a necessary starting point in the development of new technology tools to support engineering design (Milne, 2005). Therefore it is important to identify what knowledge is used in the product design process and how it is shared and utilized in product design.

1.2.1 Knowledge in Product Design

Product design is complex and multidisciplinary and it requires significant amounts of design knowledge (Rodgers & Clarkson, 1998). Engineering design tasks are mainly knowledge-intensive cognitive actions (Schmidt & Luczak, 2005). Typically, designers will use many kinds of knowledge during the design process from various areas including human factors, materials, business, manufacturing technologies and so on (Rodgers & Clarkson, 1998). The provision of this knowledge is vital to successful development of the product or system being designed, and to the future competitiveness of the company involved (Rodgers & Clarkson, 1998). Given that even the most routine of design tasks depends upon vast amounts of expert knowledge and supporting information, there is an obvious need for some sort of support which will free designers from much of the drudgery involved in searching and locating appropriate knowledge (Rodgers & Clarkson, 1998).

In attempting to design and develop high quality products efficiently, designers have to utilize a wide variety of sources of design knowledge and apply them in many different design tasks (Rodgers & Clarkson, 1998). Any knowledge support system, if it is to be truly effective throughout the design process, must facilitate all types of design knowledge (Rodgers & Clarkson, 1998). For example, during the early stages of the design process tasks such as needs identification, problem analysis and market research require both broad and shallow design knowledge. As the design progresses the required knowledge becomes more specific which may be better suited to algorithmic and deep knowledge. It is therefore important to identify and classify designers' knowledge needs when involved in new product design and development (Rodgers & Clarkson, 1998).

1.2.2 Activities in Product Design

A prominent theme in the field of design research is the study of the designer activity with an aim to improve design performance (Milne, 2005). Notable contributors to this field (e.g. Bucciarelli, 1994; Schon, 1983; Wallace & Hales, 1987) grounded their research in the study of designers as they engage in design activity. A focus on design activity can yield more understanding on how designers work together than prescriptive models of design processes (Milne, 2005). The study of activity has important implications for ICT development, especially activities related to information, though this form of research needs to be purposefully structured to obtain useful results (Milne, 2005). This research will focus on studying the design activities for the purpose of knowledge management, team collaboration and decision making activities.

1.2.2.1 Knowledge Management and Product Design

Managing knowledge is an important concern for industry (Ahmed, 2005). According to the KPMG's survey on the potential role that knowledge management can play in achieving specific organizational objectives, seventy nine percent of respondents believed that knowledge management can play a "significant" role in improving competitive advantage (KPMG, 2000). Seventy five percent believed that it is important for marketing and sixty four percent for product innovation.

Drucker (1993) defined product innovation as an application of knowledge to produce new knowledge. The product becomes a vehicle for knowledge embodiment and transfer (Sherman, Berkowitz, & Souder, 2005). Innovation in product design implies shifting attention from the product to the process of knowledge creation, sharing, and transfer (Sherman, Berkowitz, & Souder, 2005). Thus, management should give individuals and teams opportunities to apply their own knowledge and learn from others. There is hence a strong interest in mapping how knowledge transfer takes place and how it can affect design innovation (Ahmed, 2005; Sherman, Berkowitz, & Souder, 2005).

Other reasons for managing knowledge are to provide a trail for product liability legislation and to retain knowledge and experience as engineering designers retire (Ahmed, 2005). Trends in career patterns have changed and engineers change jobs more frequently nowadays (Ahmed, 2005). Therefore designers have less time to build up experience, and there will be fewer experts available for consultation in the future (Ahmed, 2005). Besides, any one designer is unlikely to become an expert in all relevant fields (Leake & Wilson, 2001). Hence, there is a need to capture, store and reuse knowledge, such as is done in the research on design history and design rationale (Ahmed, 2005). In using design rationale, novice designers may wish to understand lessons from previous experiences and experienced designers may wish to reuse design knowledge to adapt past solutions and apply these to current problems (Leake & Wilson, 2001). Designers also access information to validate design decisions, i.e. justify their decision (Kuffner & Ullman, 1991). Observations of engineering designers found that approximately 24% of a designer's time is spent acquiring and providing information (Marsh, 1997). This 24% can be broken down further: 12% of a designer's time is spent acquiring information and, up to 4% of time is spent to identify where this information is in the first place (Marsh, 1997). As knowledge is reused for many reasons, it is essential to improve knowledge management for product design (Ahmed, 2005).

1.2.2.2 Team Collaboration for Product Design

Product design is based on knowledge, and new knowledge can only be created when existing knowledge is disseminated through interaction between specialists with

varying areas of expertise (Moenaert, Caeldries, Lievens, & Wauters, 2000). It therefore comes as no surprise that ‘communication’ has occupied an important position in research on product design. Product design team members obtain information on markets, technologies, competitors, resources, technical solutions to product design problems, and translate this into a product design and product strategy (Mohrman, Finegold, & Mohrman, 2003). Consequentially, the vehicle of product design is communication (Mohrman, Finegold, & Mohrman, 2003). The productivity of product design teams depends extensively on the ability of its members to tap into an appropriate network of knowledge (Kratzer, 2001).

Efficient team collaboration is critical for decision quality as well as decision timeliness (Bajwa, Lewis, Pervan, & Lai, 2005). Inefficiencies in collaboration can prevent organizations from developing innovative ideas (Majchrzak, Rice, Malhotra, King, & Ba, 2000; Nonaka & Takeuchi, 1995). Designers face multiple tasks during product design development and team collaboration makes these processes clearer and simpler (Clark & Wheelwright, 1993; Majchrzak, Rice, Malhotra, King, & Ba, 2000). Many companies have realized the importance of team collaboration in design. For example, Cisco, created the Cisco Collaboration Center of Excellence to achieve its 2003 vision: internalize collaboration capabilities into Cisco’s culture and the day-to-day work practices of its 10,000 employees (Susman & Majchrzak, 2003).

Teamwork involves interaction among members and dissemination of timely and relevant information about each others’ expertise can improve collaboration, cohesion and commitment influencing decision making (Rico & Cohen, 2005; Stewart & Barrick, 2000). The nature of the relationship between the knowledge source and recipient facilitates team work (Dyer & Noveoka, 2000).

1.2.2.3 Decision Making in Product Design

Decision making is the main linkage between knowledge management and team collaboration for product design in any organization (Rico & Cohen, 2005; Schmidt, Montoya-Weiss, & Massey, 2001). To design a well integrated new product, decision makers must grapple with multiple product life-cycle issues, including function, geometry, manufacturability and maintainability (Powell & Buede, 2006). During

product design process, rather than just more information, designers want information in an easily accessible and usable manner (Rouse, 2002). To satisfy designer's need for knowledge, it is necessary to understand how knowledge is used to make decisions. Fundamental understanding of why and how people value knowledge is essential to maximize chances to meet their needs successfully (Rouse, 2002).

1.2.3 Product Design Space

In order to define designers' needs, it is important to understand the characteristics of design problems and the processes by which these problems are addressed (Cody, Rouse, & Boff, 1993). Design is an important subject of study in cognitive science (Goel, 1991). The idea of problem and design spaces is important in design processes (Purao, Rossi, & Bush, 2002).

The design space is a metaphoric space that contains mental representations of the developer's specific solutions, based on which he/she creates models and specifications for building the artifact (Purao, Rossi, & Bush, 2002). Newell and Simon (1972) first used the term 'problem space,' defining it as the metaphoric space wherein the problem solver moves from an initial (problem) state through intermediate states to a goal (solution) state by applying appropriate operators (Simon, 1996).

Rowe (1987) describes generative processes, or operations, that allow the designer to take knowledge states as input, or as starting positions, and produce new knowledge states as outputs. The representation of new, but incomplete states may resemble partial design solutions suggesting the existence of a separate design space (Purao, Rossi, & Bush, 2002). Problem and Design spaces provide potent perspectives to understand and improve the practice of information system development (Purao, Rossi, & Bush, 2002).

1.2.4 ICT Support for Product Design

Today ICT tools, for example, CAD tool, are developed to streamline the product design process at every stage. Early adopters have found that they have been able to enhance communications and collaboration, accelerate decision-making, improve

portfolio management, and take the paperwork out of administrative tasks (Cooper, 2003). It can also help on the front end by capturing ideas, as well as during portfolio management by automating tracking measurements of various processes (PDMA, 2004). Overall, the ICT tools can lead to better measures of product design processes in order to make better real-time decisions at the managerial level (PDMA, 2004).

Several commercial design support tools and systems are available to product designers for team collaboration, knowledge sharing and decision making by enhancing information acquisition and dissemination (DeSanctis & Poole, 1994; Griffith, Sawyer, & Neale, 2003). These tools and systems are intended to help the designer develop an understanding of the ill-structured, complex environment (Steiger, 1998). However the value of the resulting change depends on how well the tool is matched to the needs of the intended users (Cooper, 2003). Further, these support systems and tools themselves are of less value if the user is unable to exploit them to meet the defined objectives (Cooper, 2003; Majchrzak, Rice, Malhotra, King, & Ba, 2000).

1.3 Problems

The main problems in product design include:

1) Lack of understanding of knowledge in design

The use of inappropriate design knowledge can result in mistakes during product development (Rodgers & Clarkson, 1998). Time spent searching for “reliable” knowledge can also contribute to delays in the design process and may affect overall quality and product lead-times (Rodgers & Clarkson, 1998). One of the main problems with design knowledge that has been accumulated over the years is that most of it exists as separate “islands of knowledge” (Hubka & Eder, 1996). The relationship between individual knowledge elements has not been investigated adequately (Rodgers & Clarkson, 1998; Rouse, 2002). Cultural and language barriers further complicate understanding when attempting to categorize design knowledge. Thus, there is a real need for designer support that will provide the right level of knowledge at appropriate times during the design process (Rodgers & Clarkson, 1998; Rouse, 2002).

The provision of design support in a computer-based support tool requires structuring, or codification, of design knowledge (Rodgers & Clarkson, 1998). However, transferring knowledge to a computer is a difficult process because the level of detail that humans express knowledge, and that which is useful to computers, are different (Rodgers & Clarkson, 1998). In addition, the knowledge that a computer may provide is generally far too granular to be easily understood by humans (Turban, 1995). Generally speaking the structuring, or codification, of unstructured knowledge results in some loss of knowledge or information (Rodgers & Clarkson, 1998). To be of maximum use in a knowledge intensive design environment, the codified design knowledge should be made as computable as possible without compromising the original utility of the knowledge (Yoshikawa, 1993).

2) Lack of understanding of activities in design

Knowledge management: Product innovation involves synthesizing and reusing existing knowledge (Ahmed, 2005). However, skills developed during the design and development process are often lost after the project is finished (Ahmed, 2005). Consequently, mistakes are repeated and companies spend scarce resources reinventing solutions that were previously resolved. Furthermore, many organizations face difficulties in transferring knowledge from one organizational unit to another (Foote, Matson, Weiss, & Wenger, 2002). Prevailing knowledge management research lacks the dynamics to meet the different requirements from different design processes (Robert & Veryzer, 1998). Few research projects have addressed the specific view to investigate how various types of knowledge processes operate along with design processes such as team cooperation process, decision-making process and new product design process (Lang, Dickinson, & Buchal, 2002; Robert & Veryzer, 1998).

Team collaboration: Product innovation teams comprise experts from a wide variety of functions and disciplines, and this diversity can create serious barriers for shared understanding. Team members from different disciplines and different organizations or countries often lack understanding of the critical development factors for other areas. As a result, many practitioners in product design frequently feel difficult to find the right knowledge at the right time in a right way. A good mechanism to

communicate the goals of the project so that everyone can efficiently work towards a similar end is of great importance.

Decision making: Research across disciplines has focused on decision making at the individual level. Collaborative decision making has properties that are different from individual decision making such as ability of a team to generate ideas that are beyond the skills of any single team member. Collaborative decision making requires coordination between several members and stakeholders (Bajwa, Lewis, Pervan, & Lai, 2005). But decision making research at the team level is still a nascent phenomenon (Griffith, Sawyer, & Neale, 2003; Martins, Gilson, & Maynard, 2004). There is a lack of understanding of why there are many inefficient decisions due to lack of knowledge sharing, and what factors underlie decision makers' perceived needs for knowledge as a basis for formulating, choosing among, and committing to courses of action (Rouse, 2002).

3) Lack of understanding of design space

Over the years, a number of studies have been carried out to better understand “the design process” (e.g., Adelson & Soloway, 1985; Gero & Mc Neill, 1998; Guindon, 1990; Oxman, 1997; Vitalari, 1985). However, most of the studies focus only on the conceptual design phase. This may be due to the difficulty in finding experienced designers for studying system design and detailed design. As a result, designers do not have clear processes to systematically identify customer requirements and infuse them throughout the development process (Ulrich & Eppinger, 2004). Many designers frequently find it difficult to apply appropriate knowledge in different design stages (Sherman, Berkowitz, & Souder, 2005). This requires understanding the nature of the design process—who is involved, when, and what do designers do—throughout the design process (Cody, Rouse, & Boff, 1993).

4) Poor ICT support in design

New technology may offer substantial support for product design. However, there are many problems when ICT is used to support product design (Rouse, 2002). Designers usually do not act optimally because they are overwhelmed or misguided by the conflicting meanings that a design support can convey (Cooper, 2003). Simple configuration of ICT tools and systems support can mitigate these limitations but

team members training for desired ends and to solve encounters with unexpected problems is of equal importance (Clark & Wheelwright, 1993). What is worse, ICT support sometimes causes more problems to users, such as disrupting the natural flow of users' activity (Rouse, 2002). There is a lack of understanding of what types of support systems will enable designers to be better informed, and how designers will be influenced by such systems (Rouse, 2002). It is essential to have a good understanding of designers' activities so as to ensure that ICT provides valuable support for product design (Ackerman, 2002; Milne, 2005; Rodgers & Clarkson, 1998). The problems are further described in detail in literature review in Chapter 2.

1.4 Research Objectives

Based on the above analysis, it is noted that there is a need to investigate knowledge in design, to understand how designers share and utilize knowledge to make decisions in a team, and therefore use this understanding to develop a method to support the design throughout the design process. This research aims to investigate collaborative decision-making in product design. There are two aspects: optimizing team collaboration for knowledge sharing, and facilitating knowledge utilization for decision making. A product designer is the key to successful product design (Frankenberger, Badke-Schaub, & Birkhofer, 1998). However, little research has been done on product designers' cognition with respect to knowledge activities, that is, how knowledge is acquired, shared and utilized. This research focuses on the cognitive and social psychological factors of the product designer within knowledge activities (shown as Figure 1-2).

Figure 1-2 The focus of this research

The product designer's knowledge activities are influenced by many factors, see Figure 1-2. By observing and analyzing designer's cognitive needs, communication and design behavior within knowledge activities, the designer's knowledge sharing and utilization process can be studied, which can be used to formulate guidelines on how to support knowledge activities in product design (Baya & Leifer, 1996). By studying designer's team interaction, decision making behavior and performance during product design, the collaborative decision making can be better understood. This research will focus on the understanding of knowledge, activities and design space, so as to leverage on ICT support for knowledge-based collaborative decision making.

- 1) **Understanding the knowledge in design:** Knowledge is a source for guiding activities in product design, and knowledge management is essential. However, most organizations and designers do not understand what knowledge should be presented and how it can be managed. This study will explore the understanding of knowledge in product design
- 2) **Understanding the activities in design:** Design activities, for example knowledge generation, make a cognitive change in knowledge. Design activities will foster learning and knowledge transfer within and between teams during the design process. Knowledge is shared in a team, utilized for decision making, and applied to product design. Little research has addressed cognitive and social psychological factors in knowledge activities. By investigating how designers deal with knowledge, useful information for supporting design activities may be created.
- 3) **Understanding the design space:** Design space is the context in which knowledge is utilized. As designers work on the design, they make changes to the design space. Understanding of the design space will improve the use of knowledge for a better design.

Understanding the knowledge, activities and design space will be helpful to find an effective and practical methodology to support product design. It will improve team collaboration performance, help designers share knowledge and utilize the knowledge for better decision making. It will provide useful guidelines for ICT support, for example, Microsoft NetMeeting consists of a suite of client programs which enable talking (video and audio) and exchanging messages in real-time over the net, working

on documents and a whiteboard, and exchanging files, it helps the designers transfer the right knowledge to the right person. Furthermore, understanding of interactions between knowledge, activities and design space will provide more instructions for system support.

Hence, the specific aims of this research project are to:

- Identify factors for supporting knowledge-based collaborative decision making. This includes:
 - Identify knowledge-related issues that designers are concerned with in collaborative decision making in product design
 - Identify factors that should be supported in knowledge-based collaborative decision making in product design
- Develop a methodology for supporting knowledge-based collaborative decision making in product design. This includes:
 - Develop a knowledge-based collaborative decision making model for product design
 - Identify and model the knowledge in design
 - Develop a protocol coding framework for studying knowledge, activity and design space
 - Propose design implications of knowledge-based system support

This research will contribute to:

- Understanding the important factors for the support of knowledge-based collaborative decision making
- Understanding how designers approach product design activities
- Improving sharing and utilization of knowledge
- Optimizing virtual team collaboration process
- Facilitating training and learning process of novice designers
- Improving ICT support for knowledge sharing and utilization
- Supporting product innovation

1.5 Thesis Structure

This research is undertaken in three main steps: defining problems, developing a methodology and conducting experiments to validate and explore the methodology. Figure 1-3 outlines the structure of this thesis and describes the main content of each chapter.

Figure 1–3 Outline of thesis

The structure of the thesis is summarized below.

Chapter one: Introduction.

This chapter provides the background to the research together with the motivation and analyzes the main problems. The research objectives are then presented. The structure of the thesis is also outlined.

Chapter two: Literature Review and Analysis

This chapter provides the background to the research area and identifies areas for further research. Literature is reviewed in the areas of: human factors in design,

knowledge management, team collaboration, decision making, and ICT support. In each area, the advantages as well as the challenges are analyzed.

Chapter three: Research Approach

This chapter describes the overall research methodology and the research methods employed for each of the studies carried out.

Chapter four: Findings from Survey and Interviews

An online survey was conducted with nearly one hundred designers participating in the survey. Furthermore, interactive interviews were conducted with ten experienced product designers. This chapter describes the findings from the survey and interviews.

Chapter five: Methodology Development

This chapter describes a proposed method to support knowledge-based collaborative decision making. A knowledge-based collaborative decision making model for product design is presented. A knowledge modelling method is then put forward. Hypotheses are also presented.

Chapter six: Experimental Study Data Analysis Method

This chapter describes the experimental study that was conducted for validation of the hypotheses. A coding framework for data analysis is developed and validated.

Chapter seven: Results of Experimental Study

This chapter describes the experimental study results. Hypotheses are tested and other findings are presented.

Chapter eight: Results Discussion and Implications

This chapter describes the theoretical and practical implications of the research findings. The ideal cognitive supports for knowledge-based collaborative decision making are presented. It also explores new areas for future research.

Chapter nine: Discussions and Future Work

This chapter presents a summary of the research findings together with contributions. Future work is also described.

Chapter 2 Literature Review and Analysis

2.1 Introduction

This chapter reviews the literature in the following five areas of product design: (1) human factors study in design, (2) knowledge management, (3) team collaboration, (4) decision making, and (5) ICT support.

For each area, the review of literature will explore what has been done in that area. Secondly, the challenges in research are analyzed, and the main problems are summarized. The review and analysis of literature mainly focus on knowledge issues in each area. The review of knowledge management provides a background analysis of knowledge management issues. The review of team collaboration and decision making presents the analysis of knowledge sharing and utilization in both processes; and the advantage and failure in supporting product design processes are evaluated in the review of ICT support. Finally, current views on knowledge-based collaborative decision making are presented and the problems are identified in detail.

2.2 Knowledge in Product Design

Pioneering studies of knowledge management have defined knowledge in several ways. Many authors make distinctions between data, information, and knowledge as follows (Beckman, 1997; Liebowitz, 1999; Tobin, 1996).

- Data: Facts, images, or sounds constitute the database which will be interpreted and meaning attached.
- Information: filtered, formatted and summarized data. This is the basis for action and applications.
- Knowledge: represented by ideas, rules, and procedures that guide actions and decisions.

This research will focus on the knowledge in product design. Knowledge in product design is defined by the information put into a context of a particular use in this

research. It is the information evaluated and organized by the human mind for guiding actions and decisions in product design.

Different types of knowledge are recognized in the literature: explicit vs. tacit, procedural vs. declarative, esoteric vs. exoteric, shallow vs. deep (Courtney, 2001; Mitroff & Linstone, 1993; Nonaka, 1994; Nonaka & Takeuchi, 1995; Paradice & Courtney, 1989).

Many authors have described models for knowledge work process, i.e., how knowledge is created and transferred. Nonaka & Takeuchi (1995) proposed a spiral model of organizational knowledge creation that is similar to, but more sophisticated, than Bock's, see Figure 2-1. Knowledge is classified into tacit knowledge and explicit knowledge. Knowledge work process comprises social interaction and communication processes on an individual and group level. These processes are conceptualized as a knowledge spiral, a dynamic transformation-process between explicit and tacit knowledge on the different layers.

Figure 2–1 Knowledge work process as a knowledge spiral (Nonaka & Takeuchi, 1995)

The four modes of knowledge transformation process are defined as follows:

- **Socialization:** This comprises the exchange of tacit knowledge between individuals in order to convey personal knowledge and experience. Joint experience results in new shared tacit knowledge, such as common values or technical skills.

- Externalization: This describes transformation processes. On the one hand, it means the conversion of tacit into explicit knowledge, and on the other hand, the exchange of knowledge between individuals and a group. Since tacit knowledge is difficult to express, the conversion process is often supported by the use of metaphors, analogies, language rich in imagery, or stories, as well as visualization aids, like models, diagrams or prototypes. In order to stage a constructive discussion and reach creative conclusions, a deductive or inductive mode of argumentation is also very important.
- Combination: The transformation of explicit knowledge into more complex and more systematized explicit knowledge represents a combination of various pieces of knowledge. It is necessary to combine different fields of explicit knowledge and make new knowledge available on an organization-wide basis.
- Internalization: It is a process in which explicit knowledge becomes part of tacit knowledge. This can happen by automating responses. A skilled operator, for example, has difficulties expressing knowledge that used to be explicit. He just remembers what to do-the tacit expression of skilled knowledge.

The spiral model is based on the dynamic and continuous combination of the four modes of knowledge conversion. In Nonaka & Takeuchi's (1995) model, individuals interact with others to create knowledge through these four modes. Knowledge spirals from individuals to small groups to the organization and perhaps to other organizations and society in general.

Through knowledge work processes, individual knowledge is shared and the knowledge of a team reaches a higher level than the sum of the individuals' knowledge. In this research, team knowledge is viewed as existing in a collective mind, developed through interpretation, communication, and shared meanings (Courtney, 2001). Team knowledge is in a constant state of flux as new experiences are evaluated and shared.

According to Malhotra (1998), knowledge management is important for organizational adaptation, survival and competence development. In a quickly changing environment an organization must seek a synergistic combination of data

and information processing using information technologies, and the innovative capability of human beings. Knowledge Management is thus be thought of as the effort to make the knowledge available to those within the organization at the appropriate time and form in order to increase the innovative capabilities of employees.

2.3 Activities in Product Design

Design activities in knowledge-based collaborative decision making can be illustrated as in Figure 2-2.

Figure 2–2 Knowledge activities involved in knowledge-based collaborative decision making in product design

As illustrated in Figure 2-2, knowledge is the main linkage between team collaboration, decision making and ICT support for product design. It is essential to understand how these activities interact in product design, for example, how team collaboration activities interact with decision making activities.

2.3.1 Knowledge Management

2.3.1.1 Knowledge Management Process

According to Weggeman (1997), knowledge management is defined as “arranging and managing the operational processes in the knowledge value chain in such a way that realizing the collective ambition, the targets and the strategy of the organization is

being promoted”. Central to Weggeman’s work is “the knowledge value chain”. Beijerse (2000) classified knowledge management to six operational processes: (1) the determination of the necessary knowledge; (2) taking stock of the available knowledge; (3) knowledge development; (4) knowledge sharing; (5) application of knowledge; and (6) evaluation of knowledge. Based on Beijerse’s work, knowledge management process may be classified into knowledge development, knowledge acquisition, knowledge transfer, knowledge sharing, knowledge utilization and knowledge evaluation, all of which can be conceptualized as a knowledge cycle, a dynamic knowledge management process. This is illustrated in Figure 2-3.

Figure 2–3 Knowledge management process (Beijerse, 2000; Qiu, Gu, & Qiu, 2002; Weggeman, 1997)

Developing Knowledge: Before knowledge is developed, it is important to determine the necessary and available knowledge. Furthermore, one must be able to distinguish between the necessary and available knowledge. Subsequently, based on the difference, the knowledge to be developed can be determined. Knowledge can be developed via research, through education and training or by means of customer satisfaction studies.

Acquiring Knowledge: If developing the knowledge is not possible, one can decide to acquire knowledge. Knowledge to be acquired can be classified as explicit knowledge, such as literature for research and data of customers, and tacit knowledge as experiences that are created and developed from the operation of a process. Knowledge can be acquired within or outside of the enterprise and then be transferred into a knowledge warehouse in the format of electronic document as well as graphics, video clips, sound clips and others.

Transferring Knowledge: Before knowledge can be applied, it is brought to the people who need it. It is important that the correct knowledge gets to the right person at the right time. Documented knowledge can directly be transmitted by electronic mail, file transfer, or the distribution of paper documents. Another possibility is the provision of knowledge in a way that the users of this knowledge can actively access it, such as in an intranet classroom. Knowledge may be transferred through knowledge pushing, electronic publishing, knowledge subscription, education and training in intranet.

Sharing Knowledge: A crucial aspect of knowledge management is sharing the available knowledge between employees mutually, between employees and managers, between departments, etc. Knowledge sharing is primarily a knowledge work process that is greatly dependent on the culture of the organization.

Utilizing Knowledge: Utilizing knowledge for carrying out, supporting and improving value is the purpose of knowledge management. It is the central element within the knowledge management process. It should be clear that the way of utilizing knowledge may be different for different enterprises.

Evaluating Knowledge: Since knowledge can be outdated very quickly, it always needs to be updated and optimized. Through assessing, validating, filtering, editing and organizing knowledge, knowledge can then again be used as input for the determination of available and necessary knowledge. Furthermore, these activities remove irrelevant and outdated knowledge to create a high quality knowledge warehouse, which is useful for the company.

2.3.1.2 Knowledge Management Problems in Product Design

Existing knowledge is often inadequate to satisfy the information requirements for competitive new product advantage. Product design requires novel combinations of existing knowledge and solutions. It also requires the generation of new knowledge and solutions. However, at the conceptual stage of product design, unexplored design problems are hidden and will be necessary to update the knowledge when those problems emerge in later design phases. There is possible misunderstanding which may lead to a different interpretation in the knowledge exchange process. There are

difficulties in structuring and classifying the company's knowledge (Luczak & Hauser, 2005).

A literature review was conducted to identify problems in knowledge management. They were classified into four different areas: know-what, know-who, know-why and know-how, see Table 2-1.

Table 2-1 Structural issues of knowledge management in product design identified in the literature

	No.	Problems	Reference
Know-what	K1	Lack of understanding of customer needs and market situation	(Marks, 1991)
	K2	The quality of knowledge in different individual elements is different	(Rodgers & Clarkson, 1998)
	K3	Culture and language barriers further complicate understanding when attempting to categorize design knowledge and information.	(Rodgers & Clarkson, 1998)
	K4	The structuring or codification of unstructured knowledge results in some loss of knowledge of information.	(Rodgers & Clarkson, 1998)
Know-who	K5	Knowledge exists as separate “islands of knowledge”.	(Hubka & Eder, 1996)
	K6	The relationships between the individual knowledge elements have not been investigated adequately.	(Rodgers & Clarkson, 1998)
	K7	Knowledge workers have always had the option to draw on the knowledge, but in the past such exchanges have typically been limited to small, local groups and to personal networks.	(Foote, Matson, Weiss, & Wenger, 2002)
	K8	The knowledge source’s willingness to share knowledge	(Szulanski, 2000)
	K9	Lack of top management support and commitment	(Lester, 1998)
	K10	The nature of the relationship between the knowledge source and recipient, with closer relationships more likely to facilitate transfer	(Argote, 1999; Dyer & Noveoka, 2000)
Know-why	K11	Poor communication across functional groups	(Clark & Wheelwright, 1993)
	K12	The knowledge that a computer may provide is generally far too granular to be easily understood by humans.	(Turban, 1995)
	K13	Project managers lack required product knowledge	(Lester, 1998)
	K14	Far less is known about the process of breakthrough product innovation, in which connections are made between technologies and markets that cannot be traced to a seamless lineage of existing knowledge.	(Robert & Veryzer, 1998)
Know-how	K15	Poorly designed reporting and communication structure and channels	(McDonough III & Kahn, 1996)
	K16	Inadequate ICT infrastructure for electronic communication	(Von Hippel, 1988)
	K17	Team members are reluctant to accept or try new ideas	(Afuah, 1998)
	K18	The measurement of team knowledge is replete with questions and unresolved issues	(Cooke, Salas, Cannon-Bowers, & Stout, 2000)

2.3.2 Team Collaboration

2.3.2.1 Overview of Team Collaboration

Team collaboration is crucial for the successful management of a company. Gordon (1992) reported that at least 82% of US companies work in teams, and the percentage is higher in companies with a higher number of employees. The prevalent use of teams in organization requires the development of a team-centered human resource system (Cannon-Bowers & Salas, 1997).

Brannick & Prince (1997) defined a team as comprising “two or more people with different tasks, working together adaptively to achieve specified and shared goals”. Cohen & Bailey (1997) considered a team a collection of individuals who are: “inter-dependent in their tasks; share responsibility for performance outcomes; see themselves and are seen by others as an intact social entity embedded in one or more larger social systems; and manage their relationships across organizational boundaries”. A commonly used definition of a team proposed by Salas et al. (1992) defines a team as “comprising a distinguishable set of two or more people who interact dynamically, independently and adaptively toward a common and valued goal. The team has specific assigned roles or functions to perform, and a limited life span of membership”.

Team taxonomy is useful to investigate the effect of various factors on team performance. The nature of tasks performed by a team can moderate how certain factors influence the performance. For example, the effect of team diversity on team performance may be different for a military and a design team. There are several taxonomies of teams proposed in the literature.

Cohen & Bailey (1997) identified four types of teams:

- Work teams are continuing work units that are responsible for producing goods or providing services. They are typically stable, usually full time and perform well-defined tasks. Example of work teams are manufacturing teams, mining crews, and audit teams.

- Parallel teams are individuals pooled to perform functions that the regular organization is not equipped to do. They are parallel to the organizational structure, and are usually responsible for problem solving and improvement-oriented activities. Examples are quality circles and quality improvement teams
- Project teams perform tasks that are time-limited and non-repetitive. Their work involves application of special expertise and knowledge, for example, new product teams.
- Management teams comprise managers from various areas. Their tasks are to coordinate and direct sub-units and to be responsible for overall business performance.

The classification is usually associated to the task characteristics performed by the team. In addition to the team taxonomy, teams can be differentiated according to the interdependencies required for the members to complete their tasks. As stated by Salas et al. (1992), teams fall on a continuum from highly structured, independent teams, to teams that interact minimally and perform tasks individually.

2.3.2.1.1 Team Interaction

Team interdependence implies a certain structure of team interaction, and the nature of this interaction affects the performance outcome. Understanding team independence is useful for team assessment, selection of team members, training, work design and motivation of team members (Tesluk, Zaccaro, Marks, & Mathieu, 1997).

Thompson (1967) identified three types of interdependence of work activities: pooled, sequential, and reciprocal interdependence. In view of special demands created by task performance in high risk situations like flying an airplane or operating on a patient, Tesluk et al. (1997) added a fourth form of interdependence called intensive work. Figure 2-4 illustrates four basic work flow arrangements that characterize different types of team interdependencies.

Figure 2–4 Team workflow arrangements (Tسلuk, Zaccaro, Marks, & Mathieu, 1997)

As shown in Figure 2-4, different kinds of team communication create different kinds of team workflow.

- **Pooled interdependence:** each individual contributes incrementally to overall task completion. There is minimal interdependence, communication and coordination. Thus, team performance is likely to be an additive function of individual performance.
- **Sequential interdependence:** work develops in a consistent unidirectional pattern. Team performance is not simply additive, but depends on the unidirectional interface between team members. This type of teamwork can be found in assembly lines, where team members work individually one at the time, and contribute to building the product step by step along the line.
- **Reciprocal interdependence:** this setting is similar to sequential interdependence, but with bi-directional (back and forth) feedback. Interaction among members is dynamic, and team performance is achieved through more complex interaction.
- **Intensive:** the task nature is highly dynamic and complex. Team members work very closely together and workflow is poly-directional, flexible and very

intensive, because the team repeatedly faces novel situations with new problems which have to be diagnosed and solved within the team.

The work in a concurrent design team is an example of intensive workflow. Team communication is a primary means for information exchange, coordination and feedback. Kanki & Plamer (1993) described five functions of communication: to provide information, establish inter-personal relationships, establish predictable behavior patterns, maintain attention to task and monitoring, and to facilitate management. Communication efficiency is determined by the accuracy of the shared knowledge. Dietrich (2004) determined three basic characteristics of communication:

- Reciprocity: communication is a joint action that involves more than one party.
- Cognitive cost: communication is not free as it consumes resources and energy.
- Impact: changes in the state of knowledge arise through communication.

Minneman (1991) was among early proponents in the design research community who advanced the idea that design is a socio-technical process, where teams negotiate their understanding to produce technological artifacts. Brereton et al. (1996) reported empirical evidence that “the social process strongly influenced the content of the emerging product”. The team is hence important for the practice of design as well as design research. The product outcome derives from teamwork, so any study of design produces more relevant results if it focuses on design teams.

2.3.2.1.2 Sharing Knowledge through Team Collaboration

As illustrated in Figure 2-5, knowledge operates at three different levels: strategic, tactical and operational, and there is transformation of knowledge between these levels. At the operational level, knowledge operates in a spiral - dynamic transformation process. To improve and support knowledge processing in a design team at the tactical level, one must design processes and technologies so that they are suited for knowledge processing. To facilitate and motivate knowledge management, the strategy, structure and culture should be optimally mixed at the strategic level. Strategy expresses in what direction the design team will be going in the future. A good structure of the design team can make it easier for a designer to utilize the

available knowledge. The culture is primarily targeted at the motivation of team members to share their knowledge.

Figure 2–5 Sharing knowledge in a team (adapted from Beijerse, 2000)

In order to realize the final goal of making knowledge useful for product design, the operation, tactics and strategy should be optimally mixed so as to have knowledge shared effectively.

2.3.2.2 Team Collaboration Problems in Product Design

Much work has been done to improve team environment. MacMillan (2001) described six characteristics of a high performance team: common purpose, clear roles, accepted leadership, effective processes, solid relationships and excellent communication. However, little work has been done to optimize team processes for decision making. The dynamic factors mainly exist in the following issues (Qiu, Chui, & Helander, 2004b):

- **Goals:** it must be stated clearly at the outset. With face-to-face teams, it is natural that the goals shift during discussions and interaction. Some members may be unaware of the changes, and thus, everyone should be kept updated on changes. It is important that technology can support the updating of goals.
- **Communication:** technology should support team communication, as this is the most important aspect to sustain effective teamwork. Constant updating of knowledge maintains a shared knowledge base, which will enhance situation awareness in design. Technology aids should also support meta-communication–

that is, communication about communication. This is to ensure that accurate messages are transmitted between communicating parties.

- Roles distribution: as with goals, the distribution of roles among the team members must be clear at the outset. This is to avoid duplication of efforts and also to ensure proper accountability. Access to knowledge depends on the roles the individuals play in a project team. Clear roles support Know-who so that individuals know who to ask for specific knowledge.
- Norms: norms can be acceptable or unacceptable for interaction. The cultural background has a large influence on norms. With team members from all over the world, this becomes a serious issue.
- Leadership: a good leader makes or breaks a team. In a multi-disciplinary team, such as a product design team, one must determine what role a leader should play or how important it is to have a leader in a team. A leader should be someone with a vision and someone who directs the team towards that vision. How does the system support effective leadership and common appreciation of a vision?

A literature review was conducted to identify issues in team collaboration. They were classified into know-what, know-who, know-why and know-how and were summarized in Table 2-2.

Table 2-2 Structural issues of team collaboration in product design identified in the literature

	No.	Problems	Reference
Know-what	T1	Project objectives vary throughout the project	(Clark & Wheelwright, 1993)
	T2	Activity duration is usually not accurately estimated in project planning	(Crow, 1996)
	T3	A project that is difficult in terms of scope, new technology, and complexity, is susceptible to perturbations and mismatches in team, organization, and external environment. It has a greater need for knowledge acquisition and development.	(Cooper, 2003)
Know-who	T4	Lack of shared understanding between team members	(Cormican & O'Sullivan, 2004)
	T5	Much of the greater breadth and depth of knowledge must be acquired from outside the core project team	(Cooper, 2003)
	T6	Poor communication and knowledge transfer between team members	(Cormican & O'Sullivan, 2004)
	T7	Support systems for multidisciplinary teams should facilitate collaboration across space and time.	(Rouse, 2002)
	T8	Team members are multi-tasking	(Crow, 1996)
	T9	Team structure is rigid and overly hierarchical	(Frambach, 1993)
	T10	The use of tool substantially changes the roles of team members.	(Cooper, 2003)
Know-why	T11	Tools and systems which support the cognitive and relationship building activities of teams and individuals are not widely available.	(Lang, Dickinson, & Buchal, 2002)
	T12	Project team members lack required skills and experience	(Lester, 1998)
	T13	Insufficient face-to-face discussion among team members	(McDonough III & Kahn, 1996)
Know-how	T14	Project risks are not adequately identified	(Crow, 1996)
	T15	How to acquire knowledge and manage sources of uncertainty to reduce the risk of failure of either the project or the resulting product	(Cooper, 2003)
	T16	Product design teams face pressure to reduce cycle time and development costs, without sacrificing innovation	(McDonough, Kahn, & Griffin, 1999; Pate-Cornell & Dillon, 1998)

2.3.3 Decision Making

2.3.3.1 Overview of Decision Making

According to Wickens et al. (1998), many researchers assume that decision making is a task where (a) a person must select one choice from a number of choices, (b) there is information available with respect to the choices, (c) the time frame is longer than a second, and (d) the choice is associated with uncertainty; that is, it is not clear which is the best choice. Decision making that is quick and relatively automatic is termed “intuitive”, whereas decision making that is slow, deliberate, and controlled is referred to as “analytical” (Wickens, Gordon, & Liu, 1998).

One important research trend in human factors research is the study of cognition and decision making as it occurs in real-world, dynamic and complex environments. Naturalistic decision making is defined as the way people use their experience to make decisions in field settings (Zsombok & Klein, 1997). There are many important naturalistic decision making models including: Skill, Rule, Knowledge (SRK) model (Rasmussen, 1983), Means-Ends model (Rasmussen, 1990) and Recognition-Primed Decision (RPD) model (Klein, 1999). The SRK model describes three different levels of cognitive control that might potentially be used by a person during task performance (Rasmussen, 1983; Wickens, Gordon, & Liu, 1998). The Means-Ends model describes a time trajectory of work as an engineer solves problems at various abstraction levels throughout the task performance (Rasmussen, 1990).

1) Decision Making in Design

To understand design engineer performance, it is necessary to observe engineers engaged in the design process. Rittel and Webber (1973) described IBIS, a model for organizing the deliberation process that occurs during complex decision-making. The IBIS model organizes the deliberation process into a network of three data elements, Issues, Positions, and Arguments. An issue is an identified problem to be resolved by deliberation. Each issue can have many Positions that are proposed solutions developed to resolve the issue. Each position can have any number of Arguments that support or oppose that position.

IBIS can be used for tracking the evolution of design information. In this case information is organized as issues rather than physical changes and evolution of the design object (Ullman, 2001a). Throughout the design process new issues are introduced, old issues are revisited, and some issues abandoned. What became evident was that it was not the issues themselves that were important to track, but their resolution – the decisions to resolve an issue, generate new issues, postpone issue resolution, or abandon an issue (Ullman, 2001a). Design is the evolution of information punctuated by decision-making (Ullman, 2001b). Ullman (2001b) studied what is known about the information managed during decision-making, the activities used to develop and refine the information, and strategies used to manage the activities. They summarized the predominant view of how individuals and teams manage the decision-making process.

2) *Decision-Making Model*

Ullman (2001b) presented a design decision making model based on the IBIS model, see Figure 2-6.

Figure 2–6 Design decision making activities (adapted from Ullman, 2001b)

Figure 2-6 shows the relationships of decision making activities and their relevant information. Ullman (2001a) described the issue, criteria, alternatives, evaluation and decision as follows:

Issue: An Issue is a call for action to resolve some question or a problem. An issue is defined and limited by the criteria used to measure its resolution. Issues are generally expressed as the desire to change, design, redesign, create, fix, develop, or select an object which meets a number of stated and unstated criteria. The term “object” can mean any technical or business system, assembly, part, or feature. It can refer to hardware, electric devices or software. Issues can address both the form and function of the object.

Criteria: Criteria put a limit to a number of possible solutions raised by an issue. There are two major parts to a criterion, the attributes of the alternative and a target value for the attribute. The term “criterion” is used synonymously with “requirement”, “goal” or “specification”. Criteria are developed by the issue stakeholders who are individuals responsible for the resolution of the issue. Each stakeholder has preferences for how important she/he feels that each criterion is to the successful resolution of the issue. The criteria and their importance can be assessed in a “value model”-which measures the value for each design alternative.

Alternatives: An Alternative is an option generated to address or respond to a particular issue. The goal of the decision-making is to find an alternative that the decision-makers agree to adopt. Alternatives are often called “options”, “ideas”, “proposals”, or “positions.” Any number of alternatives may be developed to resolve a design issue.

Evaluation: In this phase, evaluation information is used to determine how well an alternative resolves the issue. Evaluation involves argumentation supported by information developed through prior knowledge, analysis, experimentation, or information gathering. An argument is the rationale for either supporting or opposing a particular alternative. Argumentation measures alternatives with respect to criteria, and these arguments lead to agreements.

Decision: A decision is the agreement to adopt an alternative to resolve an issue. Decisions are dynamic; they may later be changed as criteria and preferences change, and as new alternatives are generated.

3) Strategies of Individual Decision-makers

A decision strategy is a sequence of activities used to transform initial information to a point where the decision maker views the problem as solved (Ullman, 2001b).

According to Payne, Bettman, & Johnson (1993), “an individual’s decision-making strategy is contingent on the problem (task variables, context variables), the person (cognitive ability, prior knowledge) and social context (accountability, group membership). The use of various decision strategies is an adaptive response of a limited-capacity information processor (i.e. the human) to the demands of complex task environments”. A fundamental assumption in this work is that “individuals decide how to decide by considering both the cognitive effort and the accuracy of various strategies”. In other words, they do a cost-benefit analysis in choosing a strategy (Ullman, 2001a).

According to Ullman (2001a), problems in which a choice must be made can be categorized as static or dynamic. In static choice problems, the alternatives and the criteria for choosing among them are known and can be specified. Static problems with small sets of discrete choices are studied by researchers in psychology and marketing. Static problems with continuous choices or a mix of continuous and discrete choices are routinely solved in engineering using optimization methods. However, if the alternatives and criteria are evolving during the solution of the problem, then it is a dynamic choice problem. Dynamic characteristics are common in many design problems and technical situations.

A designer uses many strategies in making choices in static problems. There are two broad categories, noncompensatory and compensatory strategies (Ullman, 2001a). Noncompensatory strategies do not allow very good performance relative to one criterion to make up for poor performance on another. In other words, no matter how good an alternative is, if it fails on one evaluative criterion, it is eliminated from consideration. One static noncompensatory strategy that is well documented is called the lexicographic strategy. Static compensatory strategies allow the decision-makers to balance the good features of an alternative with its weaker features. Compensatory strategies are characterized by aggregating the judgments across various evaluative criteria. Compensatory decisions can be evaluated using a decision matrix as in Pugh’s method (Pugh, 1990) and utility theory methods (Keeney & Raiffa, 1993). When making a decision, people are adaptive in selecting a strategy. In general, conscious decisions on how to decide are not often made. For most decision problems, people assess the situation and unconsciously decide on a strategy to be used (Klein,

1999; Ullman, 2001b). For static problems, Naude, Lockett, & Holms (1997) concluded that a method that gives the accuracy of the compensatory strategy with the effort of the noncompensatory strategy would add value to human decision-making activities.

The discussion above is limited to individuals solving static decision problems. However, many problems are dynamic with the alternatives and criteria developing as the knowledge is gained (Ullman, 2001b). Dynamic choice strategies require the designer to search for new information (Ullman, 2001b). This is especially true in engineering and business. Stauffer and Ullman (1991) showed that over two thirds of the strategies used by the design engineers were searches through the design space. In these searches, the designer collected more evidence to refine the alternatives and criteria, and to better evaluate the alternatives relative to the criteria. The searches ended when some satisfactory choice had been made in the time available (Stauffer & Ullman, 1991). Where as the static methods described above have been well studied by psychologists and marketing researchers; dynamic problems, although common, are only beginning to be addressed (Ullman, 2001b). In these types of problems, the decision maker may not be sure enough about the alternatives or the relative importance of the criteria to use the noncompensatory methods. For dynamic problems, Ullman (2001b) concluded that a method that supports compensatory strategies as information about the alternatives and criteria evolves would add value to human decision making activities.

4) Team Strategies

There has been extensive research in the psychological and sociological communities on how individuals make decisions, however, there has been substantially less research on teams reaching agreement (Ullman, 2001b). Some research has come from the engineering and business communities.

Olson et al. (1996) studied 10 software design groups of 3-7 people to find the structure of team deliberation. They observed experienced teams as they worked with four software design projects at Anderson Consulting and Microelectronics and Computer Technology Corporation (MCC). The observation time was 17 hours,

which was divided in different phases. They found that they could easily code the meetings using the IBIS model with the addition of categories for project and meeting management, summarizing and other secondary activities. The activity of “summary” is where the team restates the issues, alternatives and criteria in a simple list like fashion.

Olson et al. (1996) summarized the results in a diagram that showed the distribution of time spent in developing and working on issues, alternatives and criteria, and the transitions between them. A simplified version of this diagram is shown in Figure 2-7. Here the area of the circles corresponds to the amount of time spent in that category and the width of the arrow corresponds to the frequency of the transitions between the categories.

Figure 2–7 Distribution of time spent in developing and working on issues, alternatives and criteria, and the transitions between them (Olson et al., 1996)

As shown in Figure 2-7, Olson et al. (1996) found that 46% of all transitions between categories were in or out of “criteria” (as implied by the arrows in Figure 2-7). Similarly, 41% were in or out of “alternatives”. He also found that 2 or more

alternatives were discussed in most issues, 40% of the issues had 3 or more alternatives. Of the alternatives proposed 63% were evaluated verbally and the remainder eliminated without audible evaluation. A limitation of this data is that it is not clear what part of the data corresponds to argumentation – the evaluation of the alternatives relative to the criteria. It can be concluded from Olson' data that any support system must allow easy transitions between the major information types, that are illustrated in Figure 2-7.

Naude et al. (1997) studied a team in a brake liner manufacturing company. The researchers introduced a multi-criteria decision making (MCDM) support system. This system basically forced the team to itemize the alternatives and the attributes, weigh the attributes and evaluate the alternatives relative to attributes, and then automatically ranked the alternatives. The team used the system to solve two static, interdependent problems. One had five alternatives and nine attributes (45 relationships). The other was smaller. The team was initially shocked at the results they obtained using the system. After discussion they accepted the results as an honest reflection of their perceptions and realized that they were initially forced to make sub-optimal decisions due to cognitive limitations.

5) Utilizing Knowledge for Decision Making

Decision-making is a knowledge-intensive activity with knowledge as its raw materials, work-in-process, by-products, and finished goods. Proficiency in knowledge management is increasingly important since it enhances the competitiveness of decision makers (Holsapple, 2001). The process that knowledge is utilized for decision making is illustrated in Figure 2-8.

Figure 2–8 Utilizing knowledge to support decision making for solving problem
(Adapted from Haque, Belecheanu, Barson, & Pawar, 2000)

Figure 2-8 shows how knowledge is structured to help in problem definition, solution development and solution selection (Haque, Belecheanu, Barson, & Pawar, 2000; Kreitner & Kinicki, 2004).

2.3.3.2 Decision Making Problems in Product Design

Increasing complexity of systems is causing decision making and problem solving to become more difficult and prone to error. This makes decision making a central concern to the human factors specialist. As mentioned, it is important to understand how people make decisions, the limitations they typically experience in decision making, how time pressures and limitations affect the process, and how to design systems to support and enhance decision making.

A literature review was conducted to identify decision making problems. They were classified into know-what, know-who, know-why and know-how and were summarized in Table 2-3.

Table 2-3 Structural issues of decision making in product design identified in the literature

	No.	Constraints	Reference
Know-what	D1	Some of the richness of knowledge is likely to get lost as it travels across distant situations with lesser levels of shared context.	(Foote, Matson, Weiss, & Wenger, 2002)
	D2	How much does a respondent need to know about a situation for her answer to be meaningful?	(Foote, Matson, Weiss, & Wenger, 2002)
	D3	Unexpected technical problems	(Clark & Wheelwright, 1993)
	D4	Poor relationship with suppliers	(Frambach, 1993)
Know-who	D5	Difficulty translating information and knowledge across domains and across disciplines, limiting digestibility and hence, value.	(Rouse, 2002)
	D6	When the list of experts and potential respondents grows, people might feel uneasy just calling up someone they don't know-especially someone higher in the hierarchy.	(Foote, Matson, Weiss, & Wenger, 2002)
	D7	Knowledge support system should be provided for tracking and capturing information and knowledge generated throughout decision making processes.	(Rouse, 2002)
Know-why	D8	Poor follow up in digesting information and knowledge accessed as well as using it to inform decisions.	(Rouse, 2002)
	D9	What knowledge is actually relevant to the decision?	(Foote, Matson, Weiss, & Wenger, 2002)
	D10	To what extent should knowledge be validated before it is relied upon to make significant decisions?	(Foote, Matson, Weiss, & Wenger, 2002)
	D11	There was a lack of structured support, not only in formal management reviews (decisions), but also in many decisions made by team members outside the formal reviews with respect to the detail design and development.	(Haque, Belecheanu, Barson, & Pawar, 2000)
Know-how	D12	Emergencies are not treated proactively	(Clark & Wheelwright, 1993)
	D13	Lack of customer focus	(Cormican & O'Sullivan, 2004)
	D14	How do contributors build a reputation as a reliable source of knowledge beyond my circle of close associates? How can this reliability be recognized?	(Foote, Matson, Weiss, & Wenger, 2002)
	D15	Product design decisions are affected by many uncertainty-causing elements that confuse the decision maker to reach targeted performance.	(Buyukozkan & Feyzioglu, 2004)
	D16	The use of tool interrupts the cognitive and task processes of the individual team members.	(Cooper, 2003)

2.4 Design Space

2.4.1 Overview of Human Factors Studies in Design

Design is a prominent area in human factors study. Notable contributors to the field were summarized in Table 2-4.

Table 2-4 Overview of human factors study in design

Period	Author	Research Focus	Design Phase	Subjects	Method
Before 1990	Akin (1978, 1979)	Information processing activities in architectural design	conceptual	Individual designers	verbal protocol method
	Ullman (1988) Stauffer (1987, 1991)	Information processing system problem solving process	conceptual	Five mechanical designers (Individual)	protocol analysis
	Waldron and Waldron (1988)	Design process sequence	over a few years	Several designers (Organization)	retrospective method
	Tang (1989)	The use of shared workspace	conceptual design	Eight groups of 3 or 4 designers work on short term design tasks	discussion protocol method
1990-2000	Guindon (1990)	Early stages of the software design process	conceptual	Three experienced designers (Individual)	verbal protocol method
	Goel (1991)	Address the knowledge and cognitive processes Structure of design problem spaces	problem solving	Twelve experienced designers (Individual)	protocol analysis
	Minneman (1991)	Group engineering design practice	design practice	An industrial team with short experiments simulation	discussion protocol method
	Kuffner et al. (1991)	Information requests of mechanical design engineers doing redesign	redesign	Three professional mechanical engineers (Individual)	question protocol
	Court et al. (1993)	Determine their information requirements	conceptual design	200 engineers and designers (Individual)	questionnaire based survey
	Baya (1996)	Information handling	conceptual design	Individual engineering designers	protocol study
	Austin et al. (2001)	Test and validate a tentative design framework	conceptual design	Fifteen design professionals	experimental workshop
After 2000	Chiu (2002)	The role of organization in design collaboration	design collaboration	Cases	empirical case studies and experiments
	Milne (2005)	Team handling behavior	conceptual design	Two design teams	verbal protocols

Before 1990

Akin (1978, 1979) studied the architectural design process by using the verbal protocols method. He analyzed the information processing activities of designers and identified the relationships between design problems and the representations used. He observed that designers shifted attention among different issues frequently, and that there was a relation between the representations used and the issue being attended to. He concluded that designers exhibit eight recurring behavior patterns which he called schemata. These schemata are: instantiation, generalization, inquiry, inference, representation, goal-definition, specification and integration. He also observed that design can be characterized as top-down, breadth-first process. The designers seek solutions that adequately satisfy the requirements rather than develop optimal solutions (Simon, 1957).

Ullman et al. (1988) and Stauffer (1987, 1991) studied five mechanical designers doing non-routine tasks. Based on their analysis, they proposed an information processing system model which describes the problem solving process of a mechanical designer.

Waldron and Waldron (1988) conducted a study using the retrospective method, which analyzed the design steps after the design has been completed. They studied a large project on the design of an experimental walking machine involving several designers over a few years. They reconstructed the design process sequence retrospectively after the design process was completed. This was based on interviews with the designers and records from different stages of the design project.

Tang (1989) studied the use of shared workspace by a group doing conceptual design. Using techniques borrowed from video interaction analysis, he studied 8 groups of 3 or 4 designers working on short term design tasks. He observed that the actions of the designers could be grouped under three categories: list, draw and gesture. These actions were used to accomplish functions of generating information, storing information, expressing ideas and mediating interaction. He observed that a large portion of the actions were gestures which are not adequately handled by the existing computational support tools.

Between 1990-2000

Guindon (1990) studied the early stages of the software design process. She analyzed protocols from three experienced designers and observed that designers deviate from a strictly top-down approach in early stages of the design and display an opportunistic behavior. Using the results of her study she suggested implications for training, methods and computational environments to support early stages of the design process.

Goel (1991) studied knowledge and cognitive processes of individual designers. He analyzed protocols from 12 experienced designers (2-hour session) and identified whether the content of the statement referred to: people, purpose, behavior, function, structure, and resources. He also identified the structure of design problem spaces, and found that designers' information processing is different for different design phases.

Minneman (1991) used the discussion protocol method to study group engineering design practices. He collected data from an industrial team working on the design of a photocopier sub-system. He also conducted short experiments to simulate design communication between different divisions of a design firm (engineering, manufacturing and marketing).

Kuffner and Ullman (1991) conducted a question protocol study for three professional mechanical design engineers to determine the information requests of mechanical design engineers doing redesign. He developed a taxonomy of design information, based on the questions and conjectures raised by the designers. Design information was categorized by its nature (construction, location, operation, purpose) and topic (assembly, component, interface, feature). These nature and topic were identified as the information that should be captured, structured and made available in CAD environments for facilitating reuse.

Court et al. (1993) conducted a questionnaire based survey of over 200 engineers and designers from various industries (power generation, automotive, construction, manufacturing, agriculture and utilities) to determine their information requirements.

Baya (1996) conducted a protocol study of individual engineering designers to improve the understanding and the support of information handling during the conceptual design process. Based on the results he developed an information handling framework (IHF) for conceptual design. The IHF was used for describing information handling behavior, and describes the activities designers perform with information, and the characteristics and content of the information handled in those activities. His data included only individual designers, and thus it could not identify additional activities that would be characteristic of design teams.

After 2000

Austin et al. (2001) described an experimental workshop involving fifteen design professionals in which conceptual design activity was tracked, and subsequently mapped, in order to test and validate a tentative design framework (phase and activity model). The nature of the design progression of the various teams was captured and analysed.

Chiu (2002) used empirical case studies and design experiments to provide a basic understanding of the role of organization in design collaboration, and how it affects design communication and collaboration. The study suggests that a structured organization can facilitate design communication and consequently contribute to the success of the design project. Computer supported collaborative work requires managing design tasks as well as information flows, and supporting three levels of communication, for the individual, the group and the project.

Milne (2005) expanded Baya's (1996) framework to account for the added activities that would be present in the case of a group-user scenario. He studied verbal protocols of two design teams engaged in a co-located conceptual design activity. Through this study, he identified additional activity categories accounting for group-user activity. These new activity classifications were collectively labeled as "Team Handling Framework" (THF) to distinguish activities observed in the team context from those found in individual and team situations. Based on the IHF classification of design activities (i.e., generate, access, analyze), THF included the additional classifications, namely elaborate, verify and navigate.

There are also some studies in other areas. For example, Leplat (1990) investigated the relationships between task and activity and identified the elements for elaborating a framework for error analysis. Jones (1992) investigated design methods. Krause et al. (2006) presented a solution for the management of competences of engineers working in product design process. In summary, these studies examined the process from a variety of perspectives including: problem solving, information processing, workspace activity and collaboration. The pioneering studies can be summarized as follows:

- The studies mainly focused on the conceptual design phase
- The research objectives addressed mainly problem solving, information processing, workspace activity and collaboration
- The data collection methods were lab-studies with short-term tasks assigned to small sample of subjects
- Protocol analysis was the main technique for data analysis

It was observed that other design phases, system level and detail design, are rarely studied. There are only a few studies on knowledge, team collaboration and decision making. The interactions of knowledge and activities in product design space were rarely studied. There is no standard framework for analyzing design activities.

2.4.1.1 Abstraction and Aggregation in the Design Space

Design is a quintessential cognitive task (Goel, 1991). The activity of design involves the mental formulation of future states of affairs. The products of design activity are external representations of such possible futures. Newell and Simon (1972) described the information-processing theory of human problem solving. Basically, a designer may be viewed as an information-processing system with a problem (Goel, 1991). A task environment is the external environment, inclusive of the problems, in which the information processing system operates. A design problem space is a formalization of the structure of processing molded by the characteristics of the information processing system and the task environment (Goel, 1991). A design problem space may be defined in terms of states of problem solving, operators that move the problem solving from one state to another, and evaluation functions (Goel, 1991).

In the current research the design space is expressed by different levels of abstraction and aggregation as inspired by Rasmussen (1986, 1990). The designer's thinking activities reflect the functions and elements mentioned in his/her verbal protocol. The verbal protocol illustrates the changes in concepts he/she employed during the task and these can be described in terms of the level of abstraction and the aggregation. Operation in a design space involves an exploration of the available knowledge for achieving the immediate ends. Exploration framed by the dimensions of abstraction level and aggregation is a general feature which describes how the designer navigates in a product design domain (Rasmussen, 1990).

2.4.1.2 What-why-how-who in Design Space

Rasmussen et al. (1994) put forward a model of Why, What and How in the means-ends space of product design. This model is used to break down product or systems design from the top goal to physical form. According to Rasmussen et al. (1994), any product or systems can be broken down using five abstraction levels. "Why, what and how" appear in three abstraction levels. A designer at the intermediate "what" level can ask the question "why" and is then transferred to the abstraction level above. If he asks the question "how", he will be transferred to the abstraction level below. Team collaboration plays an important role in product design, especially in the current ICT era. It is essential for designers to know who they can communicate with and find assistance needed for their work (Qiu, Chui, & Helander, 2004a). Knowing "who" is needed in all three abstraction levels where why, what and how appear. Based on Rasmussen's model of what, why and how in the means-ends space the author therefore added "who" as illustrated in Figure 2-9.

Figure 2–9 What, why, how and who in the means-ends space of product design
(Adapted from Rasmussen, Pejtersen, & Goodstein, 1994)

Figure 2-9 illustrates the what, why, how and who interrelationships between the two dimensions of level of abstraction and level of aggregation. Based on the means-ends space of product design, team collaboration and knowledge management are emphasized. Knowledge is acquired, transferred and shared in the team. It is utilized to make a right and timely decision in design. Consequently, product designers will know better what the problem is, why the problem occurred, how to solve it and who can solve the problem. Any design requirement (what should be done) can also be considered as a goal (why) for a requirement at a lower level, as well as a means (how) for a requirement at a higher level (Rasmussen, Pejtersen, & Goodstein, 1994). If there is any problem in know-what, know-why and know-how level, the designer can look for assistance from “who”. Know-who is a hinge of know-what, know-why and know-how. The knowledge of what, why, how and who in product design is illustrated in Figure 2-10.

Figure 2-10 Knowledge of what, why, how and who in product design space.

Specifically, it is necessary to support designers to know-what, why, how and who for product design and innovation:

- **Know-what:** know what the team objective is, know what the problem to be solved is, know what knowledge should be required for solving the definitive objective/problem, and know what knowledge has not been recognized.
- **Know-why:** know why the problem has occurred; know the similarities and differences between current problem and former cases.
- **Know-how:** know how to use knowledge for solving new problem, know how to generate new solutions for different situations, know how to choose the exact solution within alternative solutions, know how to make the right decision in the right time.
- **Know-who:** know who has the required knowledge, know how much knowledge he/she has, and know whether he/she is available or not.

2.4.1.3 Applying Knowledge to Design Space

It is important to identify users' needs and to make decisions conform to the needs (Landauer, 1995). The challenge is to efficiently capture and support user needs (Klein, Kaempf, Wolf, Thorsden, & Miller, 1997). It is essential to capture users'

needs and support product designers to meet users' requirements (as illustrated in Figure 2-11).

Figure 2-11 Illustration of applying knowledge to product design

It can be seen from Figure 2-11 that knowledge is well shared in a team with the aid of tools. Meanwhile, the knowledge is utilized for supporting decision making in a team collaboration process. As a result, designers' knowledge is well applied to meet the user's need, changing the color of his mobile phone, in the final product design.

2.4.2 Problems in Product Design

Design is a knowledge driven process. Designers handle large amounts of knowledge over the course of a design process. Therefore, the quality of design and the overall productivity of the design process depend heavily on the knowledge management skills of designers. In recent years there has been an increasing deployment of computer-aided tools to support the design process in areas such as CAD, CAE, CAM. However, in most cases the tools apply to very specific domains, and are usable only in the detailed design stage and provide limited or no support for knowledge management. Existing tools for knowledge management integrate poorly with the design process and are cumbersome to use. There is a need for developing tools, methods and technology which integrates smoothly with the design process.

Earlier work has demonstrated that developing decisions that affect usability are often made without relevant human-related technical information (Cody, Rouse, & Boff, 1993). Such information pertains to the anthropometric, behavioral, performance, learning, reasoning, and social characteristics of customers. This is merely an example of the kinds of knowledge that would be useful for designers. In some instances, the knowledge is simply not available to designers, but in most cases, available knowledge is overlooked, misunderstood, or misapplied. Useful knowledge about market, technology, procedure and human is usually available, but is not being factored into development decisions. Many of these transfer failures are associated with knowledge that is external to the development team.

Designers have a huge need for information. Their needs are generated by the project requirements, conceptual developments, engineering drawings, prototypes, test data, and so on. The knowledge needs also cover project-independent sources such as past developments, new technology, regulations, principles, tools, models and data, including human-related knowledge. The evidence suggests that designers use a very small fraction of the available knowledge. By distinguishing what designers use from what they ignore, this research tries to seek to understand characteristics of knowledge that designers value. This knowledge is instrumental to improving development. Thus, support systems that enhance knowledge sharing and utilization are expected to have important usage in product domain.

2.5 ICT Support in Product Design

2.5.1 Overview of Tools for Supporting Product Design

The globalization processes are intensified due to the rapid development of ICT (Vintere, Kopeika, & Bogdanovs, 2006). Gomes et al. (2006) found that ICT could facilitate problem-based learning process. Khong & Song (2003) explored associations between potential antecedent variables, attitude, belief, impact and user satisfaction with ICT product usage. Khong & Song (2003) confirmed the importance of individual and technical characteristics in influencing ICT perceptions, attitude, and impact of usage. David & Swanson (2005) identified the users of ICT into three groups: proactive, reactive and situational. They compared the different groups and suggested the implications for management.

A multitude of commercial tools exist to help product design participants acquire, develop, and manage their knowledge. Table 2-5 summarizes tools based on functionality. The four categories of design support tools, collaboration support tools, decision making support tools and knowledge management support tools are not mutually exclusive, as many products incorporate a selection of features (Cooper, 2003; Qiu, Gu, & Qiu, 2002).

The use of design tools, such as computer-aided design (CAD) and computer-aided software engineering (CASE) enables the user to create, model, visualize, simulate, and analyze their designs. While design tools effectively capture the end results of the development process, design rationale tools capture the explanation of why the “new product” was designed the way it was, including trade-offs, assumptions, and reasoning (Regli, Hu, Atwood, & Sun, 2000).

Collaborative tools encompass a variety of functions that support group work. They include: product data and document management systems that provide the capability to store, retrieve, share, and maintain configuration and version control over text-or file-based artifacts of the design process; authoring tools, which assist in the creation of text-based products, such as requirements documents, plans, and specifications, and often provide additional lifecycle management, traceability, or reporting features; and groupware systems that facilitate communication and coordination between team members.

Decision support tools, often considered a component of groupware, are computer applications that analyze data and present it so that users can make business decisions more easily. They are based on models of the business environment and are intended to “help the decision maker develop an understanding of the ill-structured, complex environment represented by the model” (Steiger, 1998). Training systems and self-learning systems try to facilitate decision making through the improvement of individuals (decision makers).

Knowledge management tools are the physical base of knowledge management and play an important role in companies: make acquiring and accumulating knowledge convenient; help employee to compound knowledge and innovate; promote

knowledge sharing and utilizing in companies; and finally improve the competitive competence of an enterprise. Knowledge management tools exist to create, manage and use resources that have encapsulated knowledge applicable to the given product development domain. Some corporations have benefited greatly from knowledge management.

2.5.2 Problems of Tools for Supporting Product Design

Decades of ergonomics research change the consumers' criteria by which they value and choose an ICT product. Compared with the emphasis placed on new functions, reliability, and good after-service in the past, emotional response to products has become an important user requirement to improve the customer acceptance in the market (Khong & Song, 2003 ; Song, 2003). Users' emotional response to product usage is often the focus of implementation research in determining the success or failure of ICT products (Swanson, 1988; Thompson, Higgins, & Howell, 1991). Tongia & Subrahmanian (2006) examined some successes and failures in product design in the ICT area to identify the dimensions of a good design. They identified that design is influenced by many factors, such as multiple stakeholders and different contexts. Unless all of those factors are considered as an ecosystem, the full potential of ICT for development will remain elusive, and many projects will fail (Tongia & Subrahmanian, 2006).

From a technology view, there are some common problems of the tools: incomplete set of functions, poor integration with other systems and difficulty in reconstruction. Moreover, system support tools can also impose various conflicts (Cooper, 2003; Qiu, Chui, & Helander, 2004b):

- Conflict with the natural flow of decision making process: system support interrupts the cognitive decision making process of the individual team members.
- Conflict in supporting the right team member: system support does not know who it should support, and even alter the roles of team members.
- Conflict in conveying the precise knowledge: system support hides or eliminates important contextual knowledge during knowledge transferring process.

Decision makers are often unable to act properly, not because they lack knowledge, but because they are overwhelmed or misguided by the conflicting meanings that systems support convey (Cooper, 2003). Whether the value of the resulting change will be positive or negative depends on how well the tool is matched to the needs of the intended users (Cooper, 2003). The system support should be delivered in a format so as to reduce these conflicts and match the needs of the intended users. An improved understanding of design will be essential both for evaluating the effects of ICT support and for providing input into its iterative development (Kushniruk, 2001).

2.7 Conclusions

This chapter reviewed the literature in the five areas of product design: human factors study in design, knowledge management, team collaboration, decision making, and ICT support. For each area, the review and analysis of literature mainly focused on knowledge issues. Current views and the advantages of each area are described. Furthermore, challenges and problems in each area were analyzed. Problems in team collaboration, decision making and knowledge management were classified into Know-what, Know-who, Know-why and Know-how, and the problems matrix of knowledge-based collaborative decision making is summarized in Table 2-8. In Table 2-8, T1-T16, D1-D16 and K1-K18 refer to the problem IDs mentioned in Table 2-2, Table 2-3 and Table 2-1 respectively. Thus, finding a suitable methodology to support knowledge-based collaborative decision making is essential for product design.

Table 2-5 Problem matrix of knowledge-based collaborative decision making in product design

Design Activities Knowledge Levels	Team Collaboration	Decision Making	Knowledge Management
Know-what	T1, T2, T3	D1, D2, D3, D4	K1, K2, K3, K4
Know-who	T4, T5, T6 T7, T8 T9, T10	D5, D6 D7	K5, K6 K7, K8 K9, K10
Know-why	T11, T12, T13	D8 D9, D10, D11,	K11, K12, K13, K14
Know-how	T14, T15, T16	D12, D13, D14, D15, D16	K15, K16, K17, K18

From the literature review it was found that structuring knowledge into chunks is an important consideration for the development of a method of support for designers. Technology aids, team environment and designers play essential roles for facilitating knowledge sharing and team collaboration. The review of decision making literature found that most studies were focused on the individual rather than a team operation. A review of computer tools found that there is no efficient support for product designers to share and utilize knowledge. The literature review identified a need to understand further how designers carry out development work and to use this understanding to develop a method of support for designers.

Based on the literature review, important factors for the support of collaborative decision making in product design have been identified in detail. It provides the guidelines for survey and interview in chapter 3.

Chapter 3 Research Approach

3.1 Introduction

This chapter describes the research approach and the studies employed in this research project. Three studies were undertaken, namely survey, interactive interview and experiment. For each of the three studies, the following aspects are covered:

- The general research method;
- The characteristics of the study;
- The use of the research method for this research;
- The method of data analysis;
- The advantages and disadvantages of the study.

The research centers on investigating the problems defined in the literature review, identifying advantages and problems in empirical experience, applying the theoretical framework to problem characterization, gathering critical and requisite data to apply and to improve the theoretical framework. The data collection and analysis methods can be summarized as in Figure 3-1 and will be described in more detail in the following sections.

Figure 3–1 Data collection and analysis methods undertaken in this research

3.2 Characteristics of Descriptive Studies

In deciding on the study methods for this research, the following criteria were taken into account:

- Information had to be available to the researcher.
- Access to information and collection of data had to be cost-effective, current and timely.
- Data collection techniques used in the study had to minimize the bias of respondents.

In this research, a survey was first used to collect data. Coupled with the survey, interactive interviews were also conducted to get firsthand data from designers. Experimental studies are becoming increasingly common in development research, and were used as a useful way of data collection in this project. Blessing et al. (1998) identified some important characteristics of descriptive studies of how to collect data in design research. These characteristics need to be considered when assessing the findings of a particular study. The three studies undertaken in this research are mapped onto these characteristics in Table 3-1.

Table 3-1 Characteristics of studies conducted

Characteristics	Options	Characteristics of studies conducted /to be conducted		
		Surveys	Interviews	Experiments
Environment	Industry, Laboratory	Industry	Industry	Industry, Laboratory
Nature of Study	Exploratory research: Research to identify the influencing factors where no prescriptive methods or tools are introduced.	Comparative-exploratory research	Exploratory Research	Comparative-exploratory research
	Comparative-exploratory research: Exploratory research that compares cases with different characteristics.			
Data Collection Methods	Real-time methods such as: observation, participant observation and thinking aloud protocols	Retrospective: Web-based survey, email/mail survey and group administered survey	Retrospective: Structured and semi-structured interviews	Real-time: participant observation (with thinking aloud), electronic monitoring and examination of records
	Retrospective methods such as: introspection, diary keeping, archival research, questionnaires and interview techniques			
Subjects	Level of individual/team	101 experienced designers and 5 teams	10 experienced designers and 5 teams	5 teams
Team Size	Number of subjects working in one case	4 per team	4 per team	4 per team
Time Constraint	Limits imposed on development time for subjects	No	No	Yes
Duration	Length of process studied	15-20 min per individual designer, 15-20 per team (3 times)	60 min per individual designer, 60 min per team (3 times)	100 min per team (3 times)
Continuation	Was the process observed continuously?	No	No	Yes
Role of Researcher	Contribution of researcher	Questionnaire designer	Interviewer	Observer
Development Object Type	Original, variant, redesign	Variant	Variant	Original
Topic	Object to be developed/task	Individual designer: Variant Team: One original project (3 phases)	Individual designer: Variant Team: One original project (3 phases)	One original project (3 phases)
Batch Size	Mass, large batch, small batch, one-off	Large	Batch	Batch

3.3 Study one: Survey

3.3.1 Purpose

The survey was conducted for identifying the problems designers face in knowledge sharing and utilization in collaborative decision making for product design. The survey was designed to specifically answer three questions:

- What are the important knowledge-related issues that designers are concerned with in collaborative decision making in product design?
- What are the important factors that should be supported in collaborative decision making in product design?
- How can one support collaborative decision making in product design?

3.3.2 Method

3.3.2.1 Subjects

The intended target group was experienced designers. To make accurate estimates based on a random sampling of designers, the following requirements were met in the sampling process (Salant & Dillman, 1994):

- Questions are asked in ways that enable people in the sample to answer willingly and accurately
- The characteristics of the designers selected in the sampling process but who do not participate in the survey are similar to those who do
- The sample is large enough to yield the desired level of precision

One hundred and one responses were received in total with 63 online responses and 38 email responses, corresponding to a response rate of twenty percent. The respondents' experience in design was surveyed. The results were summarized in Table 3-2. The results showed that most respondents had more than one year of experience in product design. Thus, most respondents had a good perception of problems in product design and could provide valuable suggestions for supporting design. The sampling may be considered a well-defined population selection with relatively high quality and stringency. At the same time, the requirements proposed by

Salant and Dillman (1994) were met adequately, resulting in a high level of confidence in the results.

Table 3-2 Analysis of respondents' experience in product design

Experience	Number of Respondents	Percentage of Sample
Less than one year	11	12.0
1-3 years	45	48.9
3-5years	22	23.9
5 years above	14	15.2
Total	92	100

3.3.2.2 Questionnaire design

A questionnaire was used for survey. Questions were mapped into three categories: questions about product design activities, team collaboration and decision making. All the questions focused on knowledge management activities. They dealt with knowledge identification, knowledge acquisition, knowledge transfer, knowledge sharing, knowledge utilization and knowledge evaluation in product design process. There were 32 questions (see Appendix 2). In addition, background information about respondents was collected. This study used a 7-point Likert scale with one indicating "strongly disagree" and seven indicating "strongly agree", see Table 3-3. The questionnaire was pilot tested.

Table 3-3 Response categories

1	2	3	4	5	6	7
Totally disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Totally agree

3.3.2.3 Procedures

An internet-based survey was used to collect data. A main advantage of an internet-based survey is that a wide geographical area can be covered in the survey. The respondents accessed the questionnaire on the Internet and were required to key in a username and password. The questionnaire was written with HTML (Hypertext Markup Language) and ASP (Active Sever Page), and was placed as a Webpage in URL. A simple tabular form was produced for ease of responding. The draft questionnaire was developed, reviewed, and pre-tested prior to final dissemination.

The questionnaire URL together with username and password was e-mailed to designers in many large companies, including IBM, Intel, GE, Motorola, Nokia and etc. Four hundred and ninety emails were sent out to designers, most of them living in Singapore and China, and some in USA, Germany and Philippines. In this way, respondents could complete the questionnaire at their own convenience and at their own pace. Respondents to the survey were asked to assess the level of criticality of the problems by rating the relevant statements from 1 to 7 according to the Likert scale.

3.3.2.4 Data analysis

The final results were input to Microsoft Excel, and the data sheets were transferred to SPSS (Statistical Programs for Social Sciences) for analysis. Principal components analysis was used for data analysis. Mean and standard deviation were calculated. The results will be presented in Chapter 4.

3.4 Study two: Interactive Interview

3.4.1 Purpose

Interactive interviews were conducted to identify the problems of knowledge sharing and utilization in collaborative decision making during product design. Interviews aimed at gaining more detailed information from experienced designers by asking questions with scenarios.

3.4.2 Method

3.4.2.1 Subjects

For the interview on knowledge-based collaborative decision making, the background information of the interviewees is illustrated in Table 3-4.

Table 3-4 Background analysis of the designers interviewed

No.	Years of Experience	Job Title	Length of Project	Interview Setting	Duration of Interview
1.	6	Product design Leader	6-12 months	Personal face to face	55 min
2.	15	Product design Leader	1-6 months	Personal face to face	55 min
3.	5	Senior Industrial Designer	3-4 months	Personal face to face	65 min
4.	5	Technical Manager	0.5-4 months	Personal face to face	50 min
5.	12	Senior Industrial Designer	2-3 months	Personal face to face	58 min
6.	8	Project Manager	3 months	Net meeting	60 min
7.	13	Senior Designer	6-12 months	Net meeting	60 min
8.	10	product design Leader	6-12 months	Net meeting	60 min
9.	4	Customer Experience Director	6-12 months	Personal face to face	52 min
10.	3	Requirements Manager	12 months	Personal face to face	50 min

Table 3-4 shows that all the interviewees were experienced in their specialty positions. The designers were considered to be particularly knowledgeable in product design. All the interviewees were working in product development, and most of them in renowned multi-national companies. Some of them were working in supervisory roles of a product design team. Designer 9 and 10 did not develop products directly, but they were in charge of analyzing customers' requirements and feedback and then transferring the knowledge to other designers. Hence, responses from them were valuable to gain a better understanding of the knowledge sharing and collaboration process in product design.

3.4.2.2 Questionnaire design

Interviews were conducted to elicit respondents' opinions and attitudes. Therefore, most interviews used open-ended questions. The interview questions are given in Appendix 3.

3.4.2.3 Procedures

Ten experienced designers were interviewed. Seven designers were interviewed face to face and three designers were interviewed over the internet, using NetMeeting. Face-to-face interviews were conducted in a meeting room. The designers were

interviewed individually and the interviews were audio-recorded. The interviewer recorded the respondents' answers on a previously developed interview schedule, see Appendix 3. Each interview took about 1 hour.

3.4.2.4 Data analysis

Information recorded from the interactive interview was subsequently deciphered for further systematic categorization. Various types of information were obtained from the interactive interview. Some of them were found to be closely related. Through careful cause-and-effect analysis, diversified information was categorized, and major factors in each category were selected for quantitative analysis. The transcripts were analyzed to compare the findings with those from surveys. The results will be presented in Chapter 4.

3.5 Study three: Experiments

3.5.1 Purpose

One way to gather data without asking questions to the respondents is to observe people in their natural work environment and record their natural behavior (Sekaran, 1984). Experimental study is most useful for studying a “small unit” such as a small group of designers.

The experimental study was conducted to test the hypotheses in the methodology developed. The aim of the experimental study was to gain an understanding of how designers approach design activities. In this study, the author observed the product design process from conceptual design, through system level design, to detail design.

This study will answer the following questions:

- 4) What kind of knowledge is handled by designers?
- 5) What are the different activities that designers perform with knowledge?
- 6) How is the knowledge used, and for what purpose in design space?
- 7) Are there any significant correlations between knowledge, activities, and design space?

- 8) What methods or tools will make it possible to improve knowledge management in the design process?

3.5.2 Method

3.5.2.1 Subjects

For the experimental study, the background information of the participants is illustrated in Table 3-5.

Table 3-5 The background information of the experimental study participants

Team No.	Code	Sex	Age (years)	Design Experience (years)	Job Title	Duration of Experimentals
1	G1-A	Male	29	6	Product Engineer	9 hours (3 hours per phase)
	G1-B	Male	28	5	Product Engineer	9 hours (3 hours per phase)
	G1-C	Male	41	18	Senior Product Engineer	9 hours (3 hours per phase)
	G1-D	Female	29	5	Product Engineer	9 hours (3 hours per phase)
Average			31.75	8.5		
2	G2-A	Male	27	5	Product Engineer	9 hours (3 hours per phase)
	G2-B	Male	31	7	Product Engineer	9 hours (3 hours per phase)
	G2-C	Male	28	7	Product Engineer	9 hours (3 hours per phase)
	G2-D	Male	31	5	Product Engineer	9 hours (3 hours per phase)
Average			29.25	6		
3	G3-A	Male	28	6	Senior Product Engineer	9 hours (3 hours per phase)
	G3-B	Male	28	5	Product Engineer	9 hours (3 hours per phase)
	G3-C	Male	27	5	Product Engineer	9 hours (3 hours per phase)
	G3-D	Female	28	5	Product Engineer	9 hours (3 hours per phase)
Average			27.75	5.25		
4	G4-A	Male	28	8	Product Engineer	9 hours (3 hours per phase)
	G4-B	Male	29	5	Product Engineer	9 hours (3 hours per phase)
	G4-C	Male	31	6	Product Design Leader	9 hours (3 hours per phase)
	G4-D	Male	29	6	Product Design Manger	9 hours (3 hours per phase)
Average			29.25	6.25		
5	G5-A	Male	30	5	Product Engineer	9 hours (3 hours per phase)
	G5-B	Male	31	6	Product Engineer	9 hours (3 hours per phase)
	G5-C	Female	28	5	Product Engineer	9 hours (3 hours per phase)
	G5-D	Male	33	11	Product Design Leader	9 hours (3 hours per phase)
Average			30.5	6.75		
Total Average			29.7	6.55		

As shown in Table 3-5, all the participants were professional designers with at least 5 years of experience. Most of them were from leading companies in China or even the

world. All five teams were currently working design teams of their respective companies. Team members inside one team knew each other well. Each team member was in charge of a different area in design. However, the software engineers and marketing people were excluded from the group, since the designers were provided the basic marketing information, and the design task is an innovative design. This study mainly focused on studying designers' behavior.

All the teams were involved in consumer product design. Team 1, 2 and 3 were experienced in transportation device design. Team 4 and 5 were experienced in electronic entertainment device design. During the experiments, all the teams were required to develop a portable entertainment device. Teams 1, 2 and 3 were required to develop a cycling device, whereas teams 4 and 5 were required to develop an electronic entertainment device. Both tasks were consumer product design. Furthermore, the design teams were allowed to develop the products according to their expertise. All the teams were required to develop an innovative concept first. However, the new product should be within their company's general background. Therefore the similarity of the products designed was controlled. They also had the knowledge to provide a detail design.

3.5.2.2 Task Design

The tasks were three consecutive design tasks, namely conceptual design, system level design and detail design (see Appendix 4). Experimental study was mainly focused on the subjects' behavior and communication in the three product design phases. Task description provided background information of the task, and there was no correct answers. Participants were asked to develop and make decisions based on their own preferences and frames of references.

3.5.2.3 Procedures

The experiments were conducted in a test room, where observers could watch without disturbing the events in the test room. Onscreen 'actions' of the designers were recorded with picture-in-picture video to a monitor and video recorder. Five teams with four experienced designers were asked to design a portable entertainment device

in three consecutive 3-hour sessions, namely conceptual design, system-level design and detail design.

Each team member was provided with a written task description (see Appendix 4). A brief presentation about tools to be used was provided, which gave the participants an insight into how to apply and use the tools. The design process was observed and all activities were recorded. Self-assessment and short group interviews were also conducted after the experimental study (see Appendix 5, 6, 7). To motivate subjects to participate seriously, they were given some monetary compensation for their participation, and the best design team was awarded some gifts.

All teams worked productively and reached a relatively successful conclusion within the prescribed time. In the debriefing after the working session, they reported that they were reasonably happy with what they had achieved in the available time. There were no overt signs of frustration or dissatisfaction within individual members of the team.

3.5.2.4 Data analysis

Verbal protocol analysis was used for data analysis. The verbal protocol method was firstly developed to study human problem solving behavior (Newell & Simon, 1972). The approach of using protocol analysis to improve the understanding of the design process is gaining momentum in design research. The design process is very complex and it is very easy to be overwhelmed by the number of variables which affect the outcome of a design process (Baya, 1996). Protocol analysis makes it possible for researchers to reduce the complexity and to look at the design process from a perspective of their interest within a controlled environment (Baya, 1996). In other words it allows researchers simulate the design process in a laboratory and collect rich and explicit data.

After the experiment was conducted, the verbal communication was transcribed in Chinese. The transcripts were segmented into knowledge fragments. Subsequently, the knowledge fragments were analyzed by a coding framework developed, a few lines at a time, to summarize the designers' activities. The duration, the number of

words transcribed, and the quantity of knowledge fragments that were analyzed are summarized in Table 3-6.

Table 3-6 The duration, numbers of words transcribed and knowledge fragments segmented in experimental study

Team No. \ Design Phase		Conceptual Design	System Level Design	Detail Design	Total
1	Duration (Min)	100	100	100	<i>300</i>
	Words Transcribed	11248	10464	11662	<i>33374</i>
	Knowledge Segmented Fragment	231	258	234	<i>723</i>
2	Duration (Min)	100	100	100	<i>300</i>
	Words Transcribed	24633	19285	17075	<i>60993</i>
	Knowledge Segmented Fragment	343	315	240	<i>898</i>
3	Duration (Min)	100	100	100	<i>300</i>
	Words Transcribed	8744	9376	8066	<i>26186</i>
	Knowledge Segmented Fragment	169	252	241	<i>662</i>
4	Duration (Min)	100	100	100	<i>300</i>
	Words Transcribed	23290	28403	8535	<i>60228</i>
	Knowledge Segmented Fragment	284	331	143	<i>758</i>
5	Duration (Min)	100	100	100	<i>300</i>
	Words Transcribed	15046	13334	6661	<i>35041</i>
	Knowledge Segmented Fragment	289	274	172	<i>735</i>
Total	<i>Total Time=1500 min</i> <i>Total Words Transcribed=215822</i> <i>Total Knowledge Fragments Segmented=3776</i>				

The data analysis method for the experimental study will be described in detail in Chapter 6. The results will be presented in Chapter 7.

3.6 Conclusions

Three approaches were employed for this study. The direction of the studies and methods of analysis were determined by the data. Each research approach had its limitation. However, they all provide supporting information to other studies. The experiments provided an understanding of how designers approached design activities. The experiment using thinking aloud is a time consuming method of data collection, but the data collected is rich in details. Surveys and interviews, due to their retrospective nature, are not as useful as an experimental study, but they are easier to conduct. All the methods of data analysis will have to involve a certain amount of

subjectivity. However, findings from the studies will be useful for the development and adjustment of methodology for support product design. Findings from the survey and interviews of knowledge-based collaborative decision making will be presented in Chapter 4.

Chapter 4 Findings from Survey and Interviews

4.1 Introduction

Based on literature review, a survey and an interview of experienced designers were conducted. The objective was to understand factors that confine or contribute to knowledge sharing and knowledge utilization in collaborative decision making in product design. Qualitative and quantitative research techniques were utilized to analyze the data. The survey and interview results statistically highlight the most critical factors that confine or contribute to the knowledge sharing and utilization process in collaborative decision making of product design. Propositions were also presented for improvement of knowledge-based collaborative decision making in design.

4.2 Findings from Survey

4.2.1 Analysis of Background Information

All the respondents had more than one year experience in product design, and they all possessed at least a Bachelor's degree in engineering. The average project duration was close to 10 months. Results showed that different companies used different tools for product design. However, the tools for communication were quite similar: Local area network (LAN) connections, Internet, E-mail and telephone were the most common communication tools. Lotus Notes Data Bases, videoconference, net meeting and etc. were also used by many respondents for communication in product design.

4.2.2 Factor Analysis

Survey results were analyzed using factor analysis to find the main factors for support of collaborative decision making, including knowledge-related issues that designers were concerned about and the factors that should be supported in collaborative decision making in product design.

Statistical Programs for Social Sciences (SPSS) was used for factor analysis. A principal components analysis was performed with Varimax rotation. By using

Kaiser's criterion, eight factors were extracted. The Kaiser-Meyer-Olkin (KMO) statistic is a measure of sampling adequacy and varies between 0 and 1 (Kaiser, 1974). A value close to 1 indicates that patterns of correlations are relatively compact and so factor analysis should yield distinct and reliable factors. This study obtained 0.763, which is greater than 0.5 and is judged as acceptable. Values above 0.7 are good (Hutcheson & Sofroniou, 1999). The Bartlett's test of sphericity produced $\chi^2=1427$, $df = 496$, and $p<0.0001$. A significant test tells that the correlation matrix is not an identity matrix and factor analysis is therefore appropriate.

The eigenvalues associated with each factor represent the variance explained by that particular linear factor. All factors with eigenvalues greater than 1 were extracted, which leaves eight factors. Rotation has the effect of optimizing the factor structure and one consequence for these data is that the relative importance of the eight factors is equalized. Factor loading of each variable is illustrated in Table 4-1. Based on the content of questions that load onto the same factor, the common themes of the questions were identified and interpreted. It can be seen from Table 4-1, the questions that load highly on factor 1 all related to difficulty in collaborative decision making, and therefore factor 1 was interpreted as '*difficulty in collaborative decision making(DCDM)*'. Likewise, factor 2 was interpreted as '*support for virtual team collaboration (SVTC)*'; factor 3 was named '*difficulty in knowledge sharing (DKS)*'; factor 4 was called '*support for decision making(SDM)*'; factor 5 was interpreted as '*dynamic team objective(DTO)*', factor 6 was named '*team performance optimization (TPO)*'; factor 7 was interpreted as '*customer needs (CN)*'; and factor 8 was interpreted as '*evaluation and communication (EC)*'.

Table 4-1 Factor loading of each variable with varimax rotation

Item	Variable	Factor							
		1	2	3	4	5	6	7	8
V1	Trust of teammates' knowledge	0.78	-0.07	0.14	-0.08	0.14	-0.04	-0.04	0.10
V2	Team members' availability	0.70	0.05	0.07	-0.07	-0.07	0.06	0.19	0.17
V3	Risks and uncertainties	0.69	-0.04	0.14	0.19	0.18	0.12	0.11	0.08
V4	Lack required knowledge	0.67	0.08	0.23	-0.19	-0.27	-0.02	0.05	0.15
V5	Relevant knowledge of past design	0.65	0.09	0.35	0.26	-0.01	-0.03	0.04	-0.20
V6	Transferring ideas	0.63	-0.13	0.09	0.30	0.07	0.06	-0.14	0.08
V7	Conflicting ideas in design	0.59	-0.07	-0.16	0.42	0.26	0.06	-0.07	0.03
V8	Personal role	0.58	-0.14	0.31	-0.02	-0.02	0.27	-0.13	0.21
V9	Misunderstanding requirements	0.53	-0.16	0.01	-0.13	-0.41	0.29	-0.17	0.29
V10	Team performance evaluation	-0.00	0.79	0.02	0.04	0.23	-0.10	0.27	0.09
V11	Information about team members	0.08	0.78	-0.11	0.15	-0.03	0.03	0.02	-0.06
V12	Organization culture	-0.04	0.72	-0.13	0.09	0.34	-0.10	-0.07	0.04
V13	Leadership	-0.10	0.70	0.07	-0.05	0.08	-0.16	0.27	-0.10
V14	Decision making process	-0.23	0.62	-0.06	0.38	0.20	0.08	-0.08	0.24
V15	Design decision making	-0.12	0.56	-0.18	0.10	0.21	0.45	0.11	-0.13
V16	Decision tasks	0.03	0.49	-0.10	0.32	-0.13	0.25	-0.05	-0.08
V17	Sharing own knowledge	0.34	-0.11	0.73	-0.31	0.02	0.12	0.07	-0.13
V18	Getting knowledge from co-workers	0.19	-0.29	0.71	-0.10	0.09	0.28	-0.12	0.06
V19	Solving unexpected problems	0.15	-0.02	0.66	0.13	0.13	-0.01	-0.46	0.03
V20	Relevant knowledge to problem	0.25	0.05	0.59	0.02	-0.28	0.07	-0.13	0.07
V21	Innovation	0.19	-0.49	0.55	0.32	0.06	-0.10	0.07	0.34
V22	Training	-0.01	0.27	-0.08	0.78	0.05	0.04	0.11	-0.03
V23	System support for decision making	0.22	0.17	0.04	0.78	0.01	-0.08	0.19	-0.06
V24	Goal setting	-0.05	0.32	0.02	0.14	0.69	0.04	0.06	-0.23
V25	Conflict with team members	0.37	0.10	0.24	-0.13	0.66	0.10	-0.02	0.16
V26	Team work process	0.12	0.36	-0.31	0.06	0.59	0.08	0.00	-0.08
V27	Feedback from customers	0.25	-0.03	0.05	0.04	-0.09	0.84	-0.00	-0.02
V28	Getting customers needs	0.01	0.00	0.28	-0.06	0.19	0.82	-0.01	0.07
V29	System support for virtual communication	-0.03	0.16	-0.06	0.22	0.13	0.07	0.78	0.36
V30	Knowledge evaluation	0.12	0.16	-0.24	0.13	-0.02	-0.06	0.76	-0.24
V31	Team innovation	0.43	-0.18	0.21	0.01	0.07	-0.02	0.11	0.73
V32	Changing team objectives	0.28	0.11	-0.09	-0.10	-0.35	0.03	-0.06	0.70

Mean of scores and standard deviation of each variable in the eight factors were computed. The mean score was used to determine the designers' attitude to the variable, while standard deviation was used to measure dispersion of data. The results are shown in Table 4-2. The factors are also displayed in terms of the percentage of variance explained (e.g., DCDM explains 14.72 % of the total variance). Totally 67.82% of variance is explained by the eight factors.

Table 4-2 Analysis of the variables of the eight factors extracted

Factor	Variable Description	Mean	S.D.	Variance Explained
DCDM				14.72 %
V7	I struggle with conflicting ideas in design	4.28	1.41	
V1	Lack of trust in teammates' knowledge	4.00	1.75	
V3	Do not know how to manage risks and uncertainties	3.97	1.52	
V2	Difficult to know team members' availability for meetings	3.90	1.50	
V4	Team members lack required knowledge for design projects	3.86	1.62	
V6	I do not know how to transfer my ideas to actual products	3.38	1.64	
V9	Teamwork objectives do not match customers' requirements	3.31	1.65	
V5	I do not have knowledge on the relevance of past design projects	3.28	1.81	
V8	I am not clear about my personal role in team collaboration	3.10	1.74	
SVTC				12.61 %
V15	Making right and efficient decisions is important for product design	6.38	0.73	
V12	The organization culture should encourage communication	6.24	0.87	
V14	It is necessary to define decision making process clearly	6.14	0.88	
V13	Leadership for virtual team collaboration is necessary	6.03	1.15	
V10	It is necessary to evaluate team performance properly	5.97	0.78	
V11	Adequate information about team members' knowledge and expertise is useful	5.90	0.77	
V16	It is necessary to define decision tasks clearly	5.79	1.50	
DKS				9.00%
V19	I have difficulty in solving unexpected problems	3.93	1.25	
V20	It is difficult to know what knowledge is actually relevant to the problem	3.55	1.79	
V18	I have difficulty in getting knowledge from my co-workers	3.31	1.29	
V17	I have difficulty in sharing my knowledge with others	3.03	1.50	
V21	I lack innovation in solving problem	2.86	1.33	
SDM				7.14%
V22	Training is useful for my decision making	5.45	1.33	
V23	System support is beneficial to my decision making	5.31	1.07	
DTO				6.86%
V24	Goal setting will improve team performance	6.24	0.83	
V26	It is necessary to define team work processes clearly	6.14	0.79	
V25	Team members have conflicting ideas	4.52	1.35	
TPO				6.29%
V28	I have difficulty in getting knowledge about customers needs	4.07	1.31	
V27	I have difficulty in getting feedback from customers	3.90	1.11	
CN				5.62%
V29	System support for virtual communication is necessary	5.41	1.15	
V30	Evaluation of team knowledge is necessary	5.07	1.41	
EC				5.57%
V32	Team objectives keep changing	4.38	1.90	
V31	Lack of team innovation	3.72	1.49	

The first few factors explain relatively large amounts of variance whereas subsequent factors explain only small amounts of variance. The eight factors in Table4-2 show that designers are concerned regarding difficulties in product design and the support for product design. The difficulties in product design include the difficulties in

collaborative decision making (factor DCDM), difficulties in knowledge sharing (factor DKS), dynamic team objective (factor DTO) and customer needs (factor CN). The support in product design includes the support for virtual team collaboration (factor SVTC), support for decision making (factor SDM), team performance optimization (factor TPO), evaluation and communication (factor EC). The results of the analysis therefore express the difficulties and supports in product design. The results are further discussed below.

Discussion on difficulties encountered in product design

Table 4-2 illustrates that the main concerns of designers were collaborative decision making, knowledge sharing, team objective and customer needs. For collaborative decision making, designers slightly disagreed that they have difficulties in knowing their personal role in team collaboration. They also disagreed that they lacked knowledge of relevant past design projects as well as team members' availability for meetings. The designers showed a neutral attitude to other issues in collaborative decision making, such as trust of team members' knowledge. Designers somewhat disagreed that they had difficulty in sharing knowledge with others. Concerning dynamic team objective, designers agreed that the team objective keeps changing, but they disagreed that they lack team innovation in product design. For customer needs, designers presented a neutral attitude to the customers' needs and feedback.

Results also show that most designers had a neutral attitude or some disagreement to the difficulties in the factors of product design. The results illustrates that some problems in product design are not as serious as many people assumed. It is necessary to know what should be supported and what should not be supported in product design so as to improve the support performance.

Discussion about the support for product design

Table 4-2 illustrates that designers were concerned about support for virtual team collaboration, support for decision making, team performance optimization, evaluation and communication. The means show that most designers strongly advocated (Mean>5) supporting product design. It implies that emphasis should be put on supporting those areas mentioned in the questions.

Concerning virtual team collaboration, designers were concerned about making efficient decisions for product design. Organizational culture, leadership and performance measurement are the main important factors and designers think should be supported. Furthermore, adequate information about team members and a clear decision task are required by designers. For the support of decision making, designers were mainly concerned about the training and system support. For team performance optimization, designers showed a strong preference in favor of team goal setting. The teamwork process must also be clearly defined. For evaluation and communication, the designers were concerned about lack of communication provided by the support system. Evaluation of knowledge was required by designers.

The eight factors identified can also help to explain the know-what, know-who, know-why and know-how in product design, as shown in Figure 4-1.

Figure 4-1 The eight factors & know-what, who, why and how

It is necessary to support know-what, know-who, know-why and know-how in product design. As illustrated in Figure 4-1, the customer needs and team objectives are mainly concerned with know-what; team collaboration and knowledge sharing address know-who; the difficulties and support for decision making are relevant to know-why; and team performance optimization, evaluation and communication deal with know-how. The results can be used to suggest good guidelines on how to support collaborative decision making process in product design, that is, the know-what, know-who, know-why and know-how in product design.

4.3 Findings from Interviews

The interviews were recorded and transcribed. The data were classified into problems and recommendations. The problems were coded according to the knowledge work process: knowledge identification, acquisition, transfer, sharing, evaluation and utilization. The recommendations were coded according to know-what, who, why and how in product design.

All interviewees agreed that it was necessary to encourage knowledge sharing, improve virtual team collaboration and use ICT to support decision making in product design. All of them were dissatisfied with the tools they used for product design. Their opinions regarding various activities in product design were consistent with the survey results. For example, one designer complained: “due to time difference, I always felt that it is difficult to communicate with my team members in the US. I can only send them email to discuss with them, but I have to wait for a long time to get reply. It is very inconvenient when something is urgent.”

The difficulties in collaborative decision making in product design were summarized as follows:

- 1) **Difficulty in identifying knowledge:** there were difficulties in identifying what knowledge was required for design. There were also difficulties in differentiating between various kinds of knowledge in product design. For example, team objectives were not clear; requirements were different for different design background; it was difficult to identify the source of knowledge.
- 2) **Difficulty in acquiring knowledge:** there were difficulties in acquiring necessary knowledge from the outside. For example, there were knowledge access problems; knowledge from customers was sometimes not reliable; it was not possible to get knowledge with full contextual descriptions.
- 3) **Difficulty in transferring knowledge:** there were difficulties in bringing knowledge to the people who needed it. For example, it was difficult to transfer knowledge to different locations/countries; sometimes designers did not know

what team members wanted; the role of team members was not clear; it was difficult to transfer knowledge top-down in the organization.

- 4) **Difficulty in sharing knowledge:** there were difficulties in sharing available knowledge between employees, between employees and managers, and between departments. These difficulties were due to many reasons. For example, there were differences in culture and language; there were conflicts in the perception of the knowledge shared; it was difficult to communicate between functions; the virtual environment reduced the motivation for knowledge sharing.
- 5) **Difficulty in evaluating knowledge:** there were difficulties in assessing, validating, filtering, editing and reorganizing knowledge. For example, cost and time constraints influenced the evaluation; evaluation criteria were lacking; the reliability of shared knowledge was unknown.
- 6) **Difficulty in utilizing knowledge:** there were difficulties in using the knowledge for carrying out, supporting and improving value-adding activities. For example, there were difficulties in selecting what knowledge affected decision making; time was limited for decision making; there were human biases in utilizing knowledge; the context was different in using knowledge.

Interviewees were also asked to give suggestions on how to support collaborative decision making in product design. One designer recommended: “sometime I don’t know what my teammates are doing on the other side of the earth, and I don’t know them well. It will be very helpful if ICT support could provide the information of my teammates and their progress in the project. Then, I could find the right people to get the right information during collaboration.” The recommendations provided by interviewees are summarized for the different knowledge levels in product design in Figure 4-2.

Figure 4–2 Recommendations for supporting collaborative decision making in product design

Figure 4-2 illustrates that it is necessary to support know-what, know-who, know-why and know-how in product design. These recommendations are also good guidelines for supporting collaborative decision making in product design.

4.4 Propositions

Thus, in order to support collaborative decision making in product design, it is essential to support team members in all the aspects of know-what, know-who, know-why and know-how. Based on these results and concepts, the findings of this study can be summarized in four propositions.

1) **Proposition: Product design team should share their knowledge about the design task.**

The results of the survey and the interview showed that designers required that teamwork objectives and decision tasks should be clearly defined. Knowledge about the task is the important input for product designer's decision making. Knowledge about the task, including customers' requirements and procedural knowledge on how to complete the task will guide team members to complete the task. By sharing knowledge about the task, the team will improve and there is a greater likelihood of

achieving the final aim. Sharing knowledge about task will be beneficial for designers to know-what in product design.

2) Proposition: Product design team should share their knowledge about team members.

The results of the survey and the interview showed designers presented strong preference on the awareness of a team, such as the affective states of team members. Knowledge about team members is also an important input for decision making in the virtual team. Shared knowledge about team members mainly refers to the perception of roles, ability, and activities of each team member in accomplishing the task (Klein, 2000). The results of the survey and the interview showed that designers often complained that they did not know what their team members were doing. This represents a lack of awareness about others' activities (Chyng, Steinfield, & Pfaff, 2002). Shared knowledge about team members is important for team members to know-who in product design, especially in virtual environment.

3) Proposition: Product design team should share the situation awareness during product design process.

The results of the survey and the interview showed that designers presented strong preference for the awareness of team situations and the teamwork process. In a dynamic environment, it is easy for the different team members to form divergent impressions without realizing it (Klein, 2000). Product design is a dynamic environment and the results of the survey and the interview showed that designers often complained that they did not really understand why team members failed to take up a suggestion, or how other team members thought about a particular contribution. Even when they did respond, it was not always clear how to interpret these responses due to difference in training, background, institutional contexts, etc. This can be considered a lack of situation awareness (Chyng, Steinfield, & Pfaff, 2002).

Situation awareness is depicted as the designer's internal model of the state of environment (Endsley, 2000). The shared situation awareness of a team refers to the degree to which the members have the same interpretation of ongoing events (Cannon-Bowers, Salas, & Converse, 1992). Product designers with shared situation

awareness have the same perception of the design environment, and similar comprehension of their meaning and the projection of their design status. A product designer can then decide what to do about the situation and carry out necessary actions. Shared situation awareness is important for team members to know-why in product design.

4) Proposition: A product design team should emphasize goal setting during the product design process.

The results of the survey and the interview showed that designers emphasized the importance of goal setting for the team. Goal setting structure is a team interactive procedure that encourages team members to align their individual goals and then generate shared team goals (Huang, Wei, Watson, & Tan, 2003). Team members have to disclose and define their individual goals and then agree on a set of team goals based on the individual goals disclosed. This involves an exchange of justification for individual as well as team goals and a ranking of proposed team goals so as to reach a consensus on final team goals that are generally shared and accepted by team members.

Goals are also central to the development of situation awareness (Endsley, 2000). Sharing knowledge is a bottom-up process for product design, whereas goal setting is a top-down processing in product design. These two processes are viewed as critical in the formation of situation awareness (Endsley, 1988, 1995). Product designers with new information may update each other on new goals that need to be activated (Endsley, 2000). Goal setting can direct designer's attention across the environment in accordance with active goals. The designer actively seeks knowledge needed for goal attainment and the goals simultaneously act as filters in interpreting the knowledge that is perceived (Endsley, 2000). Goal setting is important to guide team members to know how to make decisions to achieve the final objectives in product design.

For a design engineer, information is the resource of design. The design process is generally based on complex relationship between design factors. To make sure these relationships work efficiently, the transmission of design information is very important. Usually, data is the general form used to transport information. So keeping the effectiveness and accuracy of data becomes an important factor of consideration

during the design process. Hence, database system is an available technique to store and manage these data information. It is very easy to search or save the information. In this aspect, ICT tools can be adopted for effective and efficient decision making in the product design process. Therefore, in addition to ICT support, the quality and ownership of the knowledge are also important factors for knowledge-based collaborative decision making.

4.5 Conclusions

In this chapter, findings from a survey and an interview were presented. The survey identified eight main factors of collaborative decision making in product design. For these factors, designers showed a strong preference for clear decision tasks and team objectives, good team structure and culture, awareness of the teamwork situation and process, and the goal setting for the team. From these results one can formulate guidelines for support of collaborative decision making in product design, that is, the know-what, know-who, know-why and know-how in product design. The findings can also be used as a direction for future researchers in the areas. Based on the analysis of the results, some human factors issues were proposed for future research.

Product design is influenced by many factors. However, little research is found on product designer's cognitive activities within the knowledge activities. Future research should focus on the cognitive and social psychological factors of product designers while they are dealing with knowledge activities. Designer's cognitive needs, communication, situation awareness, decision making behavior and performance during product design should be studied in future research. The application of knowledge management in product design should be a product design strategy. In the future, the virtual environment like the internet will play a more important role in product design. It is hoped that findings presented in this chapter will help companies pay attention to knowledge management when reorganizing their team structure, and take the required knowledge structure into account when developing tools for supporting product design. It is also hoped that product designers can share their knowledge better in team collaboration and utilize their knowledge to improve design to meet customers' needs. The survey and interview also identified that knowledge quality, product ownership, together with ICT support, are important

factors in design. It is hoped that the right knowledge could be transferred to the right person during design collaboration.

To summarize, it was found that most subjects presented neutral or a little disagreement for most of the negative questions, whereas they showed strong preference on most positive questions. This illustrated that it is necessary to have positive and negative questions together so as to minimize bias of respondents. There were also some limitations of the survey and interview. For the survey, although there were nearly 100 hundred completed responses, the reliability of the data is still influenced by some external factors, such as respondents' motivation to the survey and experience in product design. For the interview, a participant may have a biased view and the data collected is restricted by what the interviewee is able to articulate. The interviewer may also be biased. The interviews with the very experienced designers proved difficult initially. Constant redirection and asking about specific projects proved a useful way to focus the interview. Each of the one-hour interviews required much more hours in travel, transcription and analysis and, hence, was the most time consuming approach.

Chapter 5 Methodology Development

5.1 Introduction

This chapter describes a methodology for knowledge-based collaborative decision making in product design. A knowledge-based collaborative decision making (KCDM) model is presented and analyzed. The knowledge in product design is identified. The knowledge processing process in product design is described. A method for modeling the knowledge in design is presented. The framework of methodology development is illustrated in Figure 5-1.

Figure 5–1 Methodology development framework

5.2 Knowledge-based Collaborative Decision Making (KCDM) Model

In this section, a conceptual model of KCDM is presented. Sharing of knowledge in team and how to utilize knowledge for decision making are described. Helander (1997) described the evolving science of ergonomics in a systematic context and presented an environment-operator-machine system. Most ergonomics problems are well described by that system approach. The systems approach can also be well applied to KCDM. The cognitive model of KCDM is presented in Fig. 5-2.

Figure 5–2 A cognitive model of KCDM in product design

KCDM can be considered a problem solving process in which the solution is a decision formed through knowledge sharing and utilization within team environment, typically leading to an action in product design. Shown as Figure 5-2, the model describes the process of KCDM in product design by considering team environment-individual-technology aid. The model includes three areas of interest in facilitating decision making: team environment, technology aid and performance measurement.

The product designer (individual) plays an essential role in the model. He/she tries to meet the users' requirements throughout the design process. Knowledge needed for decision making comes from the product designer himself/herself as well as team members. If the product designer lacks the knowledge, he/she may try to obtain that knowledge from others. Thus, the team environment is also an important part of the model.

- Team Environment: It can be conceptualized as the context in which decision making is performed. Team culture motivates team members to share their knowledge, facilitates cooperation and improves creativity. The task helps define the purpose of the team, allocates responsibility and helps make each of the team members aware of his/her role in the team. Policies, such as company strategy or public policy, have great influence on the decision making of the team members.
- Technology aid: This presents a platform for knowledge sharing, team collaboration and decision making. This helps the designer exchange knowledge with others. Decision support tools can be used to assist the product designer to make a good decision. Technology aid like PDMS is an important part of the model in the ICT era.
- Performance measurement: It is essential for the model to measure the negative outcomes brought about by requirements and limitations, such as errors and being too subjective. Likewise, it is important to measure the positive outcome brought about by capabilities and affordances, such as efficiency and quality. This facilitates individual decision making, and gives guidelines for improving team environment and leveraging on the support of technology. Finally, measures of satisfaction and affect are fed-back to the individual and thus integrated back to the model.

The individual perceives the team environment through perception, and then makes decisions for product design with the support of knowledge. Perception is guided by the individual's attention (Helander, 1997). Time and knowledge are important variables that affect perception and decision making. The individual team member makes decisions for product design under team environment with the aid of technology.

There are dependent variables and independent variables in this model. Dependent variables include ICT criteria, task performance criteria, human criteria and so forth. Independent variables are controlled by product designers, such as needs, attitudes, competence, motivation, education, experience, age and gender. Both independent and dependent variables' values will have great impact on the validity of the model. In order to improve the construct validity of the model, individuals are required to

improve their variables' value, such as ability, experience in product design. Measures of satisfaction and affect should also be objective and effective.

Figure 5-3 illustrates how the knowledge is processed for KCDM in product design.

Figure 5–3 Knowledge processing of KCDM in product design

As illustrated in Figure 5-3, knowledge is integrated into the design space by design activities, namely team collaboration, knowledge management and decision making. For KCDM, the input knowledge, for example customer requirements, is shared in a team, utilized for decision making, and thus applied to product design. Team collaboration is focused on the capture, transfer and sharing of knowledge, whereas decision making emphasizes the utilization of knowledge to make correct and timely decision. Knowledge is well managed and infused to design space. The output, for example information on design quality, will be fed-back to the designer and utilized in knowledge processing. The input knowledge, design activities and output of design space can be seen as distinct stages that affect each other in a circular ongoing cycle. In the following sections, knowledge in product design is firstly identified and classified, and then a knowledge modeling method is presented for understanding the knowledge, activities and design space.

5.3 Knowledge Identification in Product Design

5.3.1 Knowledge in Product Design

Knowledge is represented by ideas, rules, and procedures that guide decisions and actions (Beckman, 1997; Liebowitz, 1999; Tobin, 1996). “Knowledge in product

design” is defined by the information put into a context of a particular use scenario in product design. It is the information evaluated and organized by people for guiding decisions and actions in product design. Knowledge management may be thought of as the effort to make knowledge available to those who need it, in an appropriate format thereby increasing human and organizational performance (Malhotra, 1998).

5.3.1.1 Knowledge Classification

In order to meet the requirements of know-what, why, how and who in product design, it is necessary to understand what kinds of knowledge designers use for product design. Different types of knowledge is recognized in the literature: explicit vs. tacit, procedural vs. declarative, esoteric vs. exoteric and shallow vs. deep (Courtney, 2001; Mitroff & Linstone, 1993; Nonaka, 1994; Nonaka & Takeuchi, 1995; Paradice & Courtney, 1989). However, hardly any work has been done on the research of knowledge classification in product design. In this thesis, knowledge in product design is classified into four types: Market knowledge, Human knowledge, Technology knowledge and Procedural knowledge (M-H-T-P) (Qiu, Chui, & Helander, 2006). This is illustrated in Fig. 5-4.

Figure 5-4 Classification of knowledge in product design

Market knowledge (MK): represents the knowledge interacting with the external interface like customers, partners, suppliers and other stakeholders. This knowledge consists of knowledge of marketing channels, customer relationships and the strength and loyalty of these. Market knowledge is important for designer to know the objective in product design.

Technology knowledge (TK): refers to the knowledge about technologies. This form of knowledge includes inventions, publications, trademarks, patents, knowledge recipes and etc. Technology knowledge is core competence of a design team.

Procedural knowledge (PK): refers to the knowledge about how to accomplish an end. It deals with the mechanisms and structures. Procedural knowledge is the supportive infrastructure of human knowledge, technology knowledge and market knowledge.

Human knowledge (HK): represents the knowledge contained in a person, such as the skills, experience, creativity and etc. Within each designer resides the human knowledge the team seeks to utilize. Human knowledge is the source of innovation and knowledge generation.

The knowledge required in the means-ends space of product design is identified. Table 5-1 illustrates the four types of knowledge required in the designer's design thinking process. As can be seen in the Table 5-1, designers access and utilize different kinds of knowledge depending on the design space they are working in. The different kinds of knowledge vary in importance and quantity needed.

Table 5-1 Knowledge required in the Means-Ends space of product design

Knowledge Class Means-Ends	Market Knowledge	Human Knowledge	Technology Knowledge	Procedural Knowledge
Purpose	Requirements on operational need Requirements of customers Requirements of former customers Requirements of marketing	Failed idea of past design Vision Experience Skill	Requirements of past designs Performance attributes and criteria The problems with past designs Quality requirements	Former requirements definition Reason of the generation of former problem Data collection plan Past design process
Abstract Functions	Customer relationship Market constraints Task relationships Politics Culture	Creativity Heuristic Analysis of requirements Analyzing from pervious case Guess Asking colleagues for past examples Effect of no compliance with design requirements	Re-use existing suitable cases for reference Modeling of requirements Possible solutions to problems Possible function models	Re-use procedures and conditions from prior study Performance limitations Updated design requirements and state Case reasoning process Team structure External structure
General Functions	The impact of function on performance The impact of function on cost Ergonomics requirements	Modeling of functions Explanations of functions Reason from principles Input/output representations Adopt a baseline Effect of no compatibility with current design configuration Models' predictions	Functionality of past designs Modeling tools/packages Models of functionality Models' variables Adopt objects from reports Standards Relevant input/output representations	Deviations of predicted performance Modification of procedures and conditions Retrieve and adapt existing model with appropriate tools Functions generating process of past design Updated design requirements and state
Physical Functions	Criteria to be affected by function Safety requirements Reliability requirements Off-the-shelf components available Cost	Simulation of conceptual functions Simulation of design components Creativity Heuristic Adapt a baseline	Modify objects recalled from literature Experimental variables Materials Safety Reliability	Viewgraphs of design state Block diagrams of design state Updated design requirements and state
Physical Form	Forms of relative market designs Relative market prototypes/mockups Customer acceptance Credit standing	Explanations of form Brainstorm with colleagues based on his experience Drawings of forms Performance Decision alternatives selection Adopt a form	Forms of past design Forms of functions Performance data Knowledge on forms Drawing tools/packages Prototyping tools/packages Quality	Past design process (forms) Measured performance Deviations of measured performance Updated design requirements and state Decision making process

5.3.1.2 Knowledge Quality

Quality implies an inherent or distinguishing characteristic of someone or something. Depending on the background or type of product, there are different definitions of quality. For example, in software product evaluation, quality refers to the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs.

There are two different perspectives of quality: producer's perspective and customer's perspective. Quality from the producer's perspective is one of quality conformance to product design, conformance to specifications and costs. Quality is perceived to be how effectively the production process is able to conform to specifications as stated in the design. The more contemporary approach has added a new dimension and a different focus: to process quality, customer's needs and expectations must be satisfied and the customer's expectations and requirements must be central in the definition of quality. This is also known as quality from customer's perspective, which emphasize on customer expectations, requirements and value.

Cody et al. (1993) defined the concept of "value of information" in terms of benefits that the designers experiences from using the information and the costs associated with acquiring it. The concept of knowledge quality may be defined in terms of: 1). its usefulness to a designer, 2). its effectiveness associated with acquiring the knowledge, and 3). the acceptance to the designer of the available knowledge, see Figure 5-5.

Figure 5–5 Knowledge quality is a function of perceived usefulness, effectiveness and acceptance (Adapted from Cody, Rouse, & Boff, 1993)

As illustrated in Figure 5-5, knowledge quality is mainly perceived by its usefulness, effectiveness and acceptance. Six factors are assumed to contribute to knowledge quality.

- Uncertainty reduction and importance of knowledge affect usefulness.
- Ease of access and transformation requirements govern effectiveness.
- User's satisfaction and the reliability of knowledge influence acceptance.

5.3.2 Knowledge Processing in Design Space

Nonaka & Takeuchi (1995) classified knowledge as tacit and explicit knowledge. Knowledge processing in design space can be illustrated by the model in Figure 5-6.

Figure 5–6 Iceberg model of the knowledge processing in design space

As shown in Figure 5-6, knowledge in design space can also be defined as “explicit knowledge” or “tacit knowledge”, which is divided by the dashed line in Figure 5-6. The part above the dashed line refers to “explicit knowledge” in design space, whereas the part under the dashed line refers to “tacit knowledge” in design space. The designer’s internal world refers to human’s cognitive world, whereas the external world refers to the external reality. The explicit knowledge in designer’s internal world is easy to capture by analyzing the verbal communication. However, the tacit knowledge in designer’s internal world is difficult to capture. Knowledge management in design should motivate the designer to transfer the tacit knowledge into explicit knowledge.

Figuratively, let the tacit knowledge be under the sea-based, and the explicit knowledge be above the surface sea level. The designer internal world is like an iceberg in the sea, see Figure 5-6. The ice that is on top of the sea surface is the designer’s explicit knowledge. The ice that is under the sea surface is the designer’s tacit knowledge. The knowledge processing in design space is a spiraling process of interactions between explicit and tacit knowledge.

To study the knowledge cognitive processing of a designer’s internal world, the knowledge in the designer’s internal world is classified as market knowledge,

technological knowledge, procedural knowledge and human knowledge (Qiu, Chui, & Helander, 2006). Market knowledge, technological knowledge and procedural knowledge are mainly explicit. Human knowledge is mainly tacit. Only a small part of human knowledge will be externalized from tacit to explicit. During the design process, only the human knowledge that is externalized can be captured and observed.

According to Nonaka & Takeuchi (1995), knowledge creation is a spiralling process of interactions between explicit and tacit knowledge. The interactions between the explicit and tacit knowledge lead to the creation of new knowledge. The combination of the two categories makes it possible to conceptualize four conversion patterns, namely socialization (S), externalization (E), combination (C) and internalization (I) (Nonaka & Takeuchi, 1995). The definitions of the four conversion patterns are adjusted to designers from Nonaka & Takeuchi (1995) as follows:

- Socialization refers to the exchange of tacit knowledge between the designer and the external world in order to convey personal knowledge. Joint experience results in new shared tacit knowledge, such as common values or technical skills.
- Externalization describes the conversion process of tacit into explicit knowledge within the designer's internal world. Externalization requires the expression of tacit knowledge and its translation into comprehensible forms that can be understood by others. Since tacit knowledge is difficult to express, the conversion process is often supported by the use of metaphors, analogies, or stories, as well as visualization aids, like models, diagrams or prototypes.
- Combination refers to the exchange of explicit knowledge between the designer and the external world in order to convey more complex and more systematized explicit knowledge. In this stage, the key issues are communication and diffusion processes and the systemization of knowledge.
- Internalization is a process in which explicit knowledge becomes part of tacit knowledge. This can happen through learning-by-doing, and documented knowledge can play a helpful role in this process. In this process, capabilities and skills as well as firm visions and guidelines may be internalized to the designer's tacit knowledge. This tacit knowledge gained on an individual level can be shared again through socialization-processes between the designer and the external world, so that the knowledge spiral may be set in motion once more.

The spiral model is based on the dynamic and continuous entanglement of the four modes of knowledge conversion.

5.4 Knowledge Modeling in Product Design

It can be assumed that there is a knowledge space associated with the design any time in the design process (Baya, 1996). As designers work on design, they make changes to the knowledge space, either by generating, sharing, evaluating, or utilizing. A knowledge fragment may be defined as a continuous period of time during which the knowledge activity and the description of the knowledge remains the same (Baya, 1996). Each knowledge class can be segmented into fragments for modeling. The purpose of segmentation is to reduce the knowledge class into mini-topics for cognitive modeling. Each knowledge class can be segmented into knowledge fragments and modeled by the knowledge modeling framework illustrated in Figure 5-7.

Figure 5-7 Cognitive knowledge modeling framework for defining knowledge fragment

As shown in Figure 5-7, a knowledge fragment is modeled by three dimensions: action, content and context. The action dimension includes three factors: knowledge activity, team interaction and decision activity. The content dimension is defined by three factors: description, level of detail and knowledge form. The context dimension is defined by level of abstraction and aggregation in design.

For better understanding of each factor of the knowledge fragment, one hypothesis is stated for each factor. Hypotheses are focused on frequency distribution of each factor in the whole design process. Frequency refers to the number of times a designer visits

each classification during design. Time distribution is studied for understanding the period that the designer spends in each classification. Experimental study is conducted for hypotheses testing.

For knowledge class, a hypothesis may be stated for frequency distribution in design:

H1: Each knowledge class, i.e., human knowledge, market knowledge, technology knowledge and procedural knowledge, plays a different role during the three different design phases, namely conceptual design, system-level design and detail design. It is hypothesized that human knowledge and market knowledge are more important during the conceptual design as compared to the other two design phases; technology knowledge increases significantly from conceptual design to system design, and from system design to detail design; whereas procedural knowledge does not significantly change between different design phases.

5.4.1 Modeling the Content of Knowledge

A knowledge fragment is characterized by its content. Content is what is contained inside or what it is about of each knowledge fragment. It is defined by description, level of detail and form. Description identifies the properties of the design object which the designers are dealing with. Level of detail is a measure of the extent to which a knowledge fragment is clearly expressed. Knowledge form is the physical form in which the knowledge fragment exists in the knowledge space (Baya, 1996). The content dimension modelling is illustrated in Figure 5-8.

$$\text{CONTENT} = \{\mathbf{D}, \mathbf{LD}, \mathbf{KF}\}$$

Figure 5–8 The content dimension modeling framework

5.4.1.1 Description

Gunther et al. (1997) studied description frequency difference in the conceptual design phase. It was found that the descriptions such as geometry, materials, positions and linkages are of great importance in conceptual design. However, description differences in system level and detail level design have not been studied.

Shown as Figure 5-8, descriptions are categorized according to: geometry, material, position, shape/size, quality, linkage, function, kinetics, assembly, manufacturing, ergonomics, esthetics, maintenance, costs, safety, market and miscellaneous (Gunther, Frankenberger, & Auer, 1997; Pahl & Beitz, 1993). For better understanding of description in the whole design process, a hypothesis is formed about description frequency distribution in design:

H2: It is hypothesized that descriptions vary in different design phases, namely conceptual design, system-level design and detail design. It is hypothesized that market and cost are considered more frequently in conceptual design, function and geometry are considered more frequently in system level design, whereas material and shape/size are considered more frequently in detail design.

5.4.1.2 Level of detail

Design knowledge exists at various levels of detail all through the design process. However, there is no commonly agreed categorization or understanding of these levels. Baya (1996) studied designers' transfer between different levels of detail over time in conceptual design. The levels of detail were defined as unlabeled, labeled, associative, qualitative and quantitative. He found that designer moves fluidly between the different levels of detail. He inferred that designers deal with a lot of non-quantitative and non-qualitative information during the conceptual design phase.

As shown in Figure 5-8, knowledge in design evolves from the abstract to the concrete. These levels are defined from the perspective of evolution of a design concept. A concept in its initial stage exists without a label (unlabeled) and when it attains a label its level of detail increases (Baya, 1996). The level of detail increases further when the concept is associated with another concept or described qualitatively,

and the level of detail is the greatest (in its evolutionary life) when the concept is quantitatively specified (Baya, 1996).

In order to predict the transfer of levels of detail in the whole design process, a hypothesis is formed about level of detail frequency distribution:

H3: Each level of detail, i.e., unlabeled, labeled, associative, qualitative and quantitative, plays a different role in different design phases, namely conceptual design, system-level design and detail design. It is hypothesized that knowledge is mostly expressed in unlabeled level in conceptual design, associative level in system-level design, and quantitative level in detail design.

5.4.1.3 Knowledge form

As shown in Figure 5-8, there are several knowledge forms: graphic, movement, text, verbal and physical (Ullman, Herling, & Sinton, 1996).

- Graphic = Graphical, meaning drawings or sketches
- Movement = Movements by a person or physical gestures
- Text = Textual
- Verbal = Spoken words
- Physical = Physical artifacts

This study focused mainly on verbal expression, and thus hypotheses were not formed for this dimension.

5.4.2 Modeling the Action of Knowledge

Action refers to a cognitive change on a knowledge fragment. Action is defined by knowledge activities, team interaction and decision activities. Knowledge activity is referred to the action that designers perform with knowledge during design. Team interaction is used to identify the interaction process among team members during design. Decision activity is the action that designers perform in decision making during design. The action dimension modelling is illustrated in Figure 5-9.

$$\text{ACTION} = \{\text{KA}, \text{TC}, \text{DM}\}$$

Figure 5–9 The action dimension modeling framework

5.4.2.1 Knowledge activity

Baya (1996) studied the time varying behavior of designers between three information activities, namely analyze, access and generate. He found that the designer moves fluidly between the three stages, jumping back and forth in conceptual design phase. Designers spent more than half of the time in generating information and more than a quarter in accessing information. The findings confirm the belief that the conceptual design phase is mainly generative and the designer spends a considerable amount of time accessing information.

As shown in Figure 5-9, based on knowledge management process, knowledge activities are grouped into four categories: knowledge generation, knowledge sharing, knowledge evaluation and knowledge utilization (Beijerse, 2000; Qiu, Gu, & Qiu, 2002; Weggeman, 1997).

- Knowledge generation: An action which adds new knowledge to the knowledge space.
- Knowledge sharing: Sharing of the available knowledge between team members mutually.
- Knowledge evaluation: The activities of assessing, validating, filtering, editing and reorganizing knowledge.
- Knowledge utilization: Using the knowledge for carrying out, supporting and improving value-adding activities.

For understanding knowledge activities in the whole design process, one hypothesis is formed about knowledge activity frequency distribution:

H4: The various knowledge activities, i.e., knowledge generation, knowledge sharing, knowledge evaluation and knowledge utilization, play different roles in

conceptual design, system-level design and detail design. It is hypothesized that designers focus on knowledge generation and evaluation in conceptual design, knowledge sharing in system-level design, and knowledge utilization in detail design.

5.4.2.2 Team interaction

Design collaboration requires participation of individuals and coordination of design information and tasks (Chiu, 2002). Team organization is important for design collaboration, because it can affect design communication and performance (Chiu, 2002). Chiu (2002) noted that design collaboration affects design communication and collaboration. He suggested that a structured organization will facilitate design communication and contribute to the success of the design project. Collaborative work requires managing design tasks as well as information flows, and supporting three levels of communication, including individual, group and project (Chiu, 2002).

Understanding the team interaction mode will help to establish a structured organization for design project. The team interaction modes are grouped and illustrated in Figure 5-9. Team members as knowledge carriers are the central focus of knowledge management activities. Analysis of the team interaction process is beneficial for understanding the knowledge sharing behavior. For a team with 4 members, then:

- 1-way communication: refers to only one team member who is involved in the knowledge fragment.
- 2-way communication: refers to two team members who are involved in the knowledge fragment.
- 3-way communication: refers to three team members who are involved in the knowledge fragment.
- 4-way communication: refers to four team members who are involved in the knowledge fragment.

One hypothesis is formed about team interaction mode frequency distribution:

H5: Each team interaction mode, i.e., 1-way, 2-way, 3-way, 4-way communication, plays a different role in different design phases, namely conceptual design,

system-level design and detail design. It is hypothesized that team members communicate mostly in 3-way and 4-way in conceptual design, 2-way in system-level design, and 1-way in detail design.

5.4.2.3 Decision activity

Designer's decision activities have been studied by many researchers (e.g., Girod, 2000; Herling, Ullman, & D'Ambrosio, 1995; Ullman, Dietterich, & Stauffer, 1988). Decision activities are the activities that designers perform in decision making during design. Dwarakanath and Blessing (1997) compared the design process for individual designers and groups of designers. The basic decision components were categorized as Issues, Arguments, Alternatives and Decisions. It was found that groups spent more time than individuals on Issues and Arguments. They also found that individual designers spent more time on alternatives. The time spent on explicit decisions was similar for both the individuals and the groups. Ullman et al. (1996) studied the information evolution and decision making process by analyzing verbal protocol data for conceptual design. They demonstrated the usefulness in modeling design information based on objects, relationships, issues, alternatives, evaluation and decisions. They found that information is assimilated into the design space during all types of issues. Ullman et al. (1996) found that the criteria for decision making evolve as the design space under consideration changes during the design effort. The authors suggested that care needs to be exercised in development and tracking of criteria as they are provided and modified during the design process. The authors also found that development of multiple alternatives was seen early in the design process.

In this research, decision activities are grouped into objective, alternative, criteria, decision and outcome (Dwarakanath & Blessing, 1997; Herling, Ullman, & D'Ambrosio, 1995).

- Objective: any issue/topic that has to be resolved
- Alternative: an option generated by the design team for the resolution of a particular design objective
- Criteria: the yardstick against which each alternative can be compared
- Decision: statements about selecting one or more alternatives or deferring the decision to a later stage.

- Outcome: the result of implementing the decision, in terms of performance, comments, and positive or negative consequences.

For understanding decision activities in the whole design process, a hypothesis is formed about decision activity frequency distribution:

H6: Each decision activity, i.e., objective, alternative, criteria, decision and outcome, plays a different role in different design phases, namely conceptual design, system-level design and detail design. It can be hypothesized that designers focus on identifying objective and generating alternative in conceptual design, using criteria for evaluation in system-level design, and making decisions in detail design.

5.4.3 Modeling the Context of Knowledge

Context refers to the circumstances or situations in which a knowledge fragment occurs. It can be defined by level of abstraction and aggregation in product design process. Level of abstraction describes how a cognitive task can be formulated at several levels of abstraction in the representation of design properties (Rasmussen, 1990). Level of aggregation is associated with the phase of the design process to which the knowledge can be associated with (Rasmussen, 1990). The context dimension modelling is illustrated in Figure 5-10.

CONTEXT = {LAb, LAg}

Figure 5–10 The context dimension modeling framework

5.4.3.1 Level of abstraction

Cody et al. (1993) studied the process of complex system design to determine why designers often fail to consider potentially valuable technical information in making design decisions. They studied the design space from three levels of abstraction: purpose, function and form. Based upon interview and questionnaire studies, they hypothesized that design can be characterized as sequences of the activities that form paths or trajectories across levels of abstraction and aggregation in the artifact space. Moves along the levels of abstraction can be seen to represent different types of tasks. Translations along the abstraction dimension are associated with design specification (moving from higher to lower levels of abstraction), and design justification (from lower to higher). Decomposition and integration are associated with moves along the aggregation dimension (Cody, Rouse, & Boff, 1993). Findings also showed that design activities are recursive (Cody, Rouse, & Boff, 1993). For example, information needed to address a design problem often stimulates the need to have information about the information, for example, where it might be located and estimates of its validity.

Rasmussen (1990) described how a problem solving task can be formulated at several levels of abstraction in the representation of design properties. In this study the levels of abstraction are defined according to the Means-ends dimension with five abstraction levels: purpose, abstract function, generalized function, physical function and physical form. According to Rasmussen (1990), the lowest level of abstraction is represented by the physical form of the system - its material configuration. The next higher level represents the physical processes of functions of the various components and systems in a language related to their specific electrical, chemical, or mechanical properties. Above this, the functional properties are represented in more general concepts without reference to the physical process or equipment by which the functions are implemented. At the lower levels, elements in the process description match the component configuration of the physical implementation. When moving from one level of abstraction to the next higher level, the change in system properties is not merely removal of details of information on the physical or material properties. More fundamentally, information is added on higher-level principles governing the conjunction of the various functions or elements at the lower level. A change of level

of abstraction involves a shift in concepts and structure of representation as well as a change in the information suitable to characterize the state of the function or operation at the various levels of abstraction.

In other words, a low level of abstraction is related to a specific physical description and at high level to a purpose that can be met by several physical descriptions. Therefore, shifts in the level of abstraction can be used to indicate goal setting (moving up) and selection of implementation (moving down).

For understanding levels of abstraction in the whole design process, a hypothesis is formed about level of abstraction frequency distribution:

H7: Each level of abstraction, i.e., purpose, abstract function, generalized function, physical function and physical form, plays a different role in different design phases, namely conceptual design, system-level design and detail design. It is hypothesized that designers focus on purpose in conceptual design, generalized function of the product in system level design, and physical form in detail design.

5.4.3.2 Level of aggregation

Goel & Pirolli (1992) categorized design problem-solving into preliminary design, refinement, and detail design. The three problem solving phases differ at least in terms of three respects: aspects of design considered, the primary source of knowledge, and the degree of commitment made to output statements. They noted that from preliminary to detail design there was a decrease in the consideration of people, purpose, and resource aspects of design development and a corresponding increase in the structural aspect. The behavior and function aspects seemed to stay relatively constant across the three phases. They also found that there was still some input from the client at the preliminary design stage, but it disappeared by the detailed stage. There was also an increase in the number of verbalizations that were committed to paper as subjects progressed from preliminary design, through refinement, to detail design. At the same time there was an increase in the degree of explicitness and detailing in the written or drawn material. The author made a conjecture that the distinct phases result from not only the size and the complexity of the problems, but perhaps more importantly, from a combination of the different types of information

that must be considered during the design (i.e., people, purpose, behavior, function, and structure) and the different levels of detail which were considered.

Level of aggregation is associated with the phase of the design process to which the knowledge can be associated with. The product design process can be divided into conceptual design, system-level design and detail design (Ulrich & Eppinger, 2004), as illustrated in Figure 5-11.

Figure 5–11 Generic product design process (Ulrich & Eppinger, 2004)

As illustrated in Figure 5-11, in conceptual design a large set of alternative product concepts are created. Subsequently the number of alternatives is reduced until the product can be reliably produced by the production system.

During conceptual design, the market needs are identified, alternative product concepts are generated and evaluated, and a single concept is selected for further development. It is common to view the conceptual design process as comprising the following phases: customer needs identification, concept generation, concept evaluation, concept selection, concept refinement, and remaining design planning (Ulrich & Eppinger, 2004).

System-level design phase defines the product architecture, and divides the product into subsystems and components (Ulrich & Eppinger, 2004). The output of this phase is usually a geometric “layout” of the product, a functional specification of each of the product’s subsystems, and a preliminary process flow diagram for the final assembly

process (Ulrich & Eppinger, 2004). Elements of a representation are aggregated into the part-whole dimension, namely component, assembly, function unit, subsystem and whole system (Rasmussen, 1990).

Detail design includes the complete specifications of the geometry, materials, and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers (Ulrich & Eppinger, 2004). In order to study detail design, it is necessary to recognize design problems and some understanding of their common characteristic (Goel & Pirolli, 1992). The level of aggregation in detail design is divided into objective structuring, preliminary design, refinement and detail action (Goel & Pirolli, 1992).

For understanding levels of aggregation in the whole design process, a hypothesis is formed about level of aggregation frequency distribution:

H8: Each level of aggregation plays a different role in conceptual design, system-level design and detail design. It is hypothesized that concepts are mostly generated in conceptual design, whole-system is more considered in system level design, whereas details are mostly described in detail design.

5.4.4 Illustration of Knowledge Modeling

A template of knowledge modeling is illustrated in Table 5-2.

Table 5-2 Template for cognitive knowledge modeling

Knowledge Fragment: A: You know from the human factors standpoint people always like product comfortable	
Template	Cognitive Knowledge Modeling
Knowledge Class Content : Description : Detail (<i>Level of Detail</i>) : Form (<i>Knowledge Form</i>) Action : Activity(<i>Knowledge Activity</i>) : Team (<i>Team Interaction</i>) : Decision (<i>Decision Activity</i>) Context : Abstraction(<i>Level of Abstraction</i>) : Aggregation(<i>Level of Aggregation</i>)	Technological Knowledge Content : Description (<i>Ergonomics</i>) : Detail (<i>Labeled</i>) : Form (<i>Verbal</i>) Action : Activity (<i>Knowledge generation</i>) : Team (<i>1-way</i>) : Decision (<i>Criteria</i>) Context : Abstraction (<i>Physical form</i>) : Aggregation (<i>Customer needs identification</i>)

As illustrated in Table 5-2, the knowledge fragment is classified into different knowledge class, for example, the knowledge fragment in the template is classified into Technological Knowledge. Each knowledge class includes three dimensions: content, action, and context. Each dimension is modeled by few factors, which is defined in detail in above sections. More information on modeling the knowledge is introduced in Chapter 6.

5.5 Conclusions

This study takes a multidisciplinary perspective. It traverses across management, mechanical engineering and human factors engineering. Technology aids, team environment and designers play essential roles for facilitating knowledge sharing and team collaboration. Designers undertake knowledge activities with the support of technology aids within a team environment. The focus is mainly on knowledge issues in product design such as designer's knowledge access and utilization behavior and

team members' decision making behavior in product design, and how decisions are leveraged by knowledge sharing and utilization.

A KCDM model for product design was constructed. Knowledge in product design was identified, and a new classification of knowledge is put forward. The knowledge quality was defined and the importance of knowledge quality in KCDM was described. The knowledge processing in product design was described. A knowledge modeling method was presented based on the content, action and context of knowledge. The methodology is an initial investigation into the knowledge in design. Understanding of other issues needs to be addressed further in the experimental study in the following chapter 6 and 7.

Chapter 6 Experimental Study Data Analysis Method

6.1 Introduction

This chapter describes the experimental study data analysis method. A KCDM coding framework was developed for analyzing the verbal protocol.

6.2 Data Analysis Procedure

Verbal protocol analysis was used to uncover the design process of a designer team from a knowledge perspective. Clearly since the experimental study set-up was a small scale simulation of real design activity, not all knowledge handling scenarios prevalent in real life were observed during the design. However, the design scenarios were real and provide a possibility of detailed analysis of design activities. This can be used to understand knowledge handling in real world design.

After the experiments, all the data were transcribed with time stamp. The verbal communication between designers was coded according to a knowledge coding framework, which is defined in the following section. The data analysis procedure is illustrated in Figure 6-1.

Figure 6–1 Data analysis procedure

The data was segmented into knowledge fragments. The purpose of segmentation was to reduce the data into smaller chunks which were easier to handle and could be analyzed from a knowledge perspective. Knowledge fragments were defined based on its time stamp, knowledge class, description, knowledge activity, team interaction, decision activity, level of abstraction and level of aggregation. Finally, the quantitative results were obtained by statistical analysis.

6.3 KCDM Coding Framework

To better understand the notion of design behaviour and some of the definitions below, it was assumed that at any time in the design process there was a knowledge space associated with the design. As designers worked on the design, they made changes to the knowledge space, either by generating, sharing, evaluating, or utilizing.

Based on the knowledge modeling method described in chapter 5, a KCDM coding framework was developed, see Table 6-1. The coding framework includes 7 dimensions: knowledge class, description, level of detail, knowledge activity, team interaction, decision activity, level of abstraction and level of aggregation. There are also few categories in each dimension. For convenience, abbreviations in bracket were used to represent some categories in the following sections (See Table 6-1). The operational definitions for each dimension are defined below.

Table 6-1 KCDM coding framework for defining knowledge fragments

Time Stamp	Knowledge Class (KC)	Description (DP)	Level of Detail (LD)	Knowledge Activity (KA)	Team Interaction (TI)	Decision Issues (DI)	Level of Abstraction (LA)	Level of Aggregation		
								Conceptual Design (CD)	System-level Design (SD)	Detail Design (DD)
<ul style="list-style-type: none"> Start time End time 	<ol style="list-style-type: none"> Human Knowledge (HK) Technology knowledge (TK) Market Knowledge (MK) Procedural Knowledge (PK) 	<ol style="list-style-type: none"> Geometry Material Position Shape/Size Quality Linkage Function Kinetics Assemblage Manufacturing Ergonomics Esthetics Maintenance Costs Safety Market Software Miscellaneous 	<ol style="list-style-type: none"> Unlabeled(U) Labeled(L) Associative(A) Qualitative(QI) Quantitative(Qn) 	<ol style="list-style-type: none"> Knowledge Generation (KG) Knowledge Sharing (KS) Knowledge Evaluation (KE) Knowledge Utilization. (KU) 	<ol style="list-style-type: none"> 1-way 2-way 3-way 4-way 	<ol style="list-style-type: none"> Objective(O) Alternatives(A) Criteria(C) Decision(D) Outcome(Out) 	<ol style="list-style-type: none"> Purpose (P) Abstract Function (AF) Generalized Function (GF) Physical Function (PF) Physical Form (PFm) 	<ol style="list-style-type: none"> Customer needs Identification (CI) Concept Generation (CG) Concept Evaluation (CE) Concept Selection (CS) Concept Refinement (CR) Remaining design Planning (RP) 	<ol style="list-style-type: none"> Component (C) Assembly (A) Function Unit (FU) Subsystem (S) Whole System (WS) 	<ol style="list-style-type: none"> Objective Structuring (OS) Preliminary Design (PD) Refinement (R) Detail Action (DA)

6.3.1 Knowledge Class

Knowledge class was classified using four categories: human knowledge, technology knowledge, market knowledge and procedural knowledge. The definition of each knowledge class was described in Chapter 5. The coding framework for the verbal protocol analysis is defined in Figure 6-2.

Figure 6-2 Coding framework for knowledge class

6.3.2 Description

Design descriptions were classified using the following categories: Geometry, Material, Position, Shape, Quality, Linkage, Function, Kinetics, Assemblage, Manufacturing, Ergonomics, Esthetics, Maintenance, Costs, Safety, Market and Miscellaneous (Gunther, Frankenberger, & Auer, 1997; Hales & Gooch, 2004; Pahl & Beitz, 1993). The operational definitions for coding are defined in Table 6-2.

Table 6-2 Design description and its contributing factors

Description	Definition	Contributing Factors
Geometry	The mathematics of the properties, measurement, and relationships of points, lines, angles, surfaces, and solids	<i>Space, Spatial constraints, Fit of part, Surface finish</i>
Material	The substance or substances out of which a thing is or can be made	<i>New materials, Energy needed, Temperature, Pressure, Working fluid selection, Corrosion</i>
Position	The arrangement of relative location and orientation	<i>Layout, Arrangement, Stacking, Orientation</i>
Shape/Size	The characteristic surface configuration of a thing	<i>Height, Width, Length, Diameter, Weight, Form</i>
Quality	The inherent or distinctive characteristics or properties of an object, process or other thing	<i>Quality criteria, Quality assurance, Accreditation, Standards, Inspection, Labeling, Testing, Quality control, Reliability, Failures, Monitoring, Patent</i>
Linkage	A connection or relation of a series of rigid links connected with joints to form a closed chain, or a series of closed chains	<i>Tolerance, Expansion and contraction, Torque, Surface fitting, Connection, Joints</i>
Function	The action for which a thing is particularly fitted	<i>Forced involved, Motion of parts, Control system, Velocities, Outputs</i>
Kinetics	The forces and motions that characterize a system	<i>Strength, Stiffness, Dynamics, Stability, Vibration, Resonance, Residual stress, Acceleration</i>
Assemblage	The putting together of manufactured parts to make a completed product, such as a machine or electronic circuit	<i>Special regulations, Installation, Foundations, Bolting, Welding, Sequence of assembling</i>
Manufacturing	To make or process raw materials to a product, especially with the use of industrial machines	<i>Factory limitations, Means of production, Transport, Packaging, Material handling, Storage, Industrial standards</i>
Ergonomics	The physical and psychological relationship between machines and the people who use them, such as the design, manufacture, and arrangement of products and environments to be safe, healthy, and comfortable for human beings	<i>Human interface relationships, Comfort, User friendly, Lighting, Clarity, Interactions, Human behavior, Toxicity, Flammability, Age groups</i>
Esthetics	A conception of what is artistically valid or beautiful	<i>Customer appeal, Color, Texture, Fashion, Future expectations, Consistency</i>
Maintenance	The work of keeping something in proper condition	<i>Servicing intervals, Inspection, Exchange and repair, Painting, Cleaning, Recycle, Scrap, Warranty, Spare parts</i>
Costs	The expenditure of something, such as time or labor, necessary for the attainment of a goal	<i>Design costs, Reproduction, Supplier costs, Testing costs, Labor, Cost to customer, Manufacturing costs, Wastage</i>
Safety	The condition of being safe	<i>Hazard elimination, Safeguarding, Personal protection, Instructions, Training, Environment</i>
Market	The opportunity to buy or sell	<i>Size of market, Strength of market, Distribution network, Suppliers, Supplier quality and reliability, Customer expectations, Selling, Advertising, Feedback of customers, Product name, Product ownership</i>
Miscellaneous	Other issues in design	Process

6.3.3 Level of Detail

The operational definitions for coding are defined in Table 6-3. The levels are arranged in increasing order of detail, going from top to bottom (Baya, 1996).

Table 6-3 Definition of different level of detail

Level of Detail	Interpretation
Unlabeled	Referring to knowledge fragment without a name, as in an idea or a new concept
Labeled	Referring to the knowledge fragment by a name, as in using a name for a new concept
Associative	When knowledge fragment contains knowledge about relations or details with other fragment
Qualitative	When attributes of a knowledge fragment are qualitatively addressed, or when operation or motion is qualitatively described
Quantitative	When attributes of a knowledge fragment are quantitatively described

6.3.4 Knowledge Activities

Knowledge activities are grouped into four categories for coding: knowledge generation, knowledge sharing, knowledge evaluation, and knowledge utilization. The definitions of underlying activities are defined in Table 6-4.

Table 6-4 Knowledge activities and underlying activities

Knowledge Activities	Underlying Activities	Description
Knowledge Generation	Identifying	Determine what knowledge is required and the difference of different knowledge
	Externalizing	Converting tacit knowledge into explicit knowledge
	Proposing	Propose an idea or theme or with a reference to a sketch
	Construct	Arranging ideas about artifacts, methods and so forth systematically
Knowledge Sharing	Creating	Create new knowledge
	Acquiring	Acquiring necessary knowledge from team members or outside
	Locating	Determine whereabouts of knowledge
	Interpreting	Interpret the implication or meaning of a concept or idea presented in an earlier knowledge segment
Knowledge Evaluation	Referring	Refer to a sample, metaphor or former cases
	Transferring	Distribute knowledge to team members
	Assessing	Assessing an idea or concept according to some rational basis
	Validating	Validate knowledge relevance, value, and accuracy
	Filtering	Transforming information into more manageable, understandable and useful knowledge
Knowledge Utilization	Modifying	Changing the knowledge in the form or character, qualifying or limiting the meaning of knowledge so as to make more suitable or acceptable
	Reorganizing	Reorganizing knowledge or structuring knowledge
	Reasoning	Thinking rationally and logically and to draw inferences or judgments
	Combination	Transforming knowledge into more complex and more systematized
	Selecting	Choose among alternatives
	Applying	Retrieving and using knowledge in making decisions, solving problems
	Predicting	Telling about something in advance of its occurrence by means of special knowledge or inference

6.3.5 Team Interaction

The purpose of the team interaction mode is to describe the interaction process among team members during design. For a team with 4 members, the team interaction mode includes 1-way, 2-way, 3-way and 4-way communication. The 1-way interaction describes the situation when one person is talking but there is no response from others.

6.3.6 Decision Making Activities

Decision making activities are grouped into objective, alternative, criteria, decision and outcome (Dwarakanath & Blessing, 1997; Herling, Ullman, & D'Ambrosio, 1995). The underlying activities for each group are defined in Table 6-5.

Table 6-5 Decision making activities and underlying activities

Decision Making Activities	Underlying Activities
Objective	Identifying objectives Generating objectives
Alternative	Organizing objectives to be worked on Identifying alternative Clarifying the alternatives' working principles Clarifying the alternatives' environment
Criteria	Identifying criteria Refining criteria to insure understanding Weighting criteria
Decision	Choosing the best alternative Controlling the decision making process Decision what to do next
Outcome	Establishing decision performance relative to a particular criterion Gathering external information Generating analytical results

6.3.7 Level of Abstraction

The levels of abstraction are classified into purpose, abstract function, generalized function, physical function and physical form. The levels are arranged in decreasing order of abstractness, going from bottom to top in Table 6-6.

Table 6-6 Operational definition of levels of abstraction (Adapted from Rasmussen, 1990)

Level of Abstraction	Operational Definition	Example of Descriptions
Purpose	This is the highest level of abstraction. This level represents the intended functional effect of the design upon its environment. This can be done in terms of simple, quantitative input-output specifications or in terms of the environmental, functional relationships of which the design is a part.	Market relations Supply sources Safety requirements Product name Procedure Quality
Abstract Function	The overall function of a design can be represented by a generalized causal network, e.g., in terms of information, energy, or mass flow structures reflecting the intended operational state or, more specially, in terms of flow of products, commodities, or monetary value through the design.	Flow of energy and mass Energy balances Kinetics
Generalized Function	The concepts and language used for description are related to functional relationships that are found for a variety of physical configurations and have general, but typical properties. There is no tie to the physical implementation yet.	Production Manufacturing Assembly Testing Maintenance Power supply Material
Physical Function	This level represents physical (the mechanical, electrical, or chemical) function of the design or its parts. The description of functional properties is tightly related to the physical implementations, which will very often be by means of standardized technical components of widespread use. The description is focused on the specific physical equipment and the physical variables used to characterize its functional states.	Physical functioning of equipment and machinery Equipment specifications and characteristics
Physical Form	This is the lowest and most concrete level of abstraction. It is the representation of physical form, i.e., the physical appearance and configurations of the design and its parts. It includes descriptions such as pictures, perspective drawings, scale models and instruction manuals.	Form Weight Color of parts and components Building layout and appearance Shape & Size

6.3.8 Level of Aggregation

In different design phases, the levels of aggregation are different. Thus, the levels of aggregation are classified differently for coding for different design phase. In conceptual design phase, the operational definitions for different levels of aggregation are illustrated in Table 6-7. The levels are arranged in increasing order of aggregation, going from top to bottom.

Table 6-7 Operational definition of levels of aggregation in conceptual design
(Adapted from Ulrich & Eppinger, 2004)

Conceptual Design	Operational Definition
Customer needs Identification	The goal of this activity is to understand customers' needs and to effectively communicate them to the development team. The output of this step is a set of carefully constructed customer need statements, organized in a hierarchical list, with importance weightings for many or all of the needs.
Concept Generation	The goal of concept generation is to explore how product concepts address customer needs. Concept generation includes a mix of external search, creative problem solving within the team, and systematic exploration of the various solution fragments the team generates. The results of this activity are usually a set of concepts, each typically represented by a sketch and brief descriptive text.
Concept Evaluation	The evaluation of potential new product concepts during the discovery phase of a product development project. Potential concepts are evaluated for their fit with business strategy, technical feasibility, manufacturability, and potential for financial success.
Concept Selection	Concept selection is the activity in which various product concepts are analyzed and sequentially eliminated to identify the most promising concepts. The process usually requires several iterations and may initiate additional concept generation and refinement.
Concept Refinement	In this step, one or more concepts are tested and refined to verify that customer needs have been met, assess the market potential of the product, and identify any shortcomings which can be remedied during further development.
Remaining Design Planning	In this step, the team creates a detailed development schedule, devises a strategy to minimize development time, and identifies the resources required to complete the project. The major results are the economic analysis of the product, the development schedule, the project staffing, the budget and so forth.

In system-level design phase, the operational definitions for different levels of aggregation are illustrated in Table 6-8. The levels are arranged in increasing order of aggregation, going from top to bottom.

Table 6-8 Operational definition of levels of aggregation in system-level design
(Adapted from Rasmussen, 1990)

System-Level Design	Operational Definition
Component	Forming a portion, division, piece, or segment of a whole. The components of a product may include standard parts purchased from suppliers. Examples of standard components include motors, switches, electronic chips, and screws. Other components are custom parts, made according to the manufacture's design from raw materials, such as sheet steel, plastic pellets, or aluminum bars. Example: a processor chip.
Assembly	Forming a set of components that fit together to form a self-contained unit. Assembly may refer to the whole that results from the action of assembling. Modules, components or elements or combinations of such may be the objects of the assembly. Example: a printed circuit board.
Function Unit	Forming the individual operations and transformations that contribute to the overall performance of the product. Functional units are usually described in schematic form before they are reduced to specific technologies, components, or physical working principles. Example: a traffic signal controller cabinet.
Subsystem	Forming a unit or device that is part of a larger system. Example: a disk subsystem is a part of a computer system.
Whole System	Forming a group of interacting, interrelated, or interdependent elements a whole. Example: an automated traffic system.

For detail design phase, the operational definitions for different levels of aggregation are illustrated in Table 6-9. The levels are arranged in increasing order of aggregation, going from top to bottom.

Table 6-9 Operational definition of levels of aggregation in detail design (Adapted from Goel & Pirolli, 1992)

Detail Design	Operational Definition
Objective Structuring	A collection of statements that serve to solicit or generate information to structure the objective.
Preliminary Design	A collection of statements that result in the initial generation and exploration of some aspect of the design. They are accompanied by fast, fluid drawings.
Refinement	A collection of statements that serve to elaborate and further the commitment to a previously generated design idea or element. Transformation or variations of existing drawings accompany them.
Detail Action	A collection of statements that serve to detail, and give the final form to, some aspect of the design. They are accompanied by crisp, straight-lined, dimensioned drawings and so forth.

6.3.9 Template for knowledge fragment classification

The template for knowledge fragment classification is illustrated in Table 6-10.

Table 6-10 Template for knowledge fragment classification

After Segmentation 00: 25:20:24 A: You know from the human factors standpoint people always like comfortable products	
Template	Example
Knowledge-Fragment : Time (<i>Start time- End time</i>) : Class (<i>Knowledge Class</i>) : Description : Detail (<i>Level of Detail</i>) : Activity (<i>Knowledge Activity</i>) : Team (<i>Team Interaction</i>) : Decision (<i>Decision Activity</i>) : Abstraction (<i>Level of Abstraction</i>) : Aggregation (<i>Level of Aggregation</i>)	Knowledge-Fragment : Time (00252024-00252210) : Class (<i>TK</i>) : Description (<i>Ergonomics</i>) : Detail (<i>Labeled</i>) : Activity (<i>KG</i>) : Team (<i>1-way</i>) : Decision (<i>Criteria</i>) : Abstraction (<i>Physical form</i>) : Aggregation (<i>Customer needs identification</i>)

6.4 Validation of KCDM Coding Framework

Intercoder reliability is the widely used term for the extent to which independent coders evaluate a characteristic of a message or artifact and reach the same conclusion (Lombard, Snyder-Duch, & Bracken, 2002). In content analysis, intercoder agreement is measured to represent "the extent to which the different judges tend to assign exactly the same rating to each object" (Tinsley & Weiss, 2000).

In communication the most widely used indices for reliability are: Percent agreement, Holsti's method, Cohen's kappa (k) and so forth (Lombard, Snyder-Duch, & Bracken, 2002). Percent agreement seems to be used most widely and is intuitively appealing and simple to calculate, but the methodological literature is consistent in identifying it as a misleading measure that overestimates true intercoder agreement (Lombard, Snyder-Duch, & Bracken, 2002). Both the percentage agreement and Holsti's method do not account for chance agreement among raters, and thus are not adequate for use (Capozzoli, McSweeney, & Sinha, 1999).

Cohen's kappa (Cohen, 1960), on the other hand, is a statistic that assesses interjudge agreement without counting in the chance agreement. Cohen's Kappa is commonly used in research involves the coding of behavior (Bakeman, 2000). The formula for calculate the value of Cohen' Kappa is:

$$\text{Kappa} = (F0 - FC) / (N - FC)$$

Where:

N = the total number of judgments made by each coder

F0 = the number of judgments on which the coders agree

FC = the number of judgments for which agreement is expected by chance

According to Landis and Koch (1977), Kappa values greater than 0.80 indicate almost perfect agreement beyond chance, values between 0.60 and 0.80 indicate substantial agreement beyond chance, values between 0.40 and 0.60 indicate moderate agreement beyond chance, values between 0.20-0.40 indicate fair agreement beyond chance, and values less than .20 indicate poor agreement beyond chance.

The KCDM coding framework was validated by calculating intercoder reliability. A representative sample of protocol data was coded by three coders for testing intercoder reliability of the KCDM coding framework. According to Lacy and Riffe (1996), the acceptable sample size of knowledge fragments for coding is 30 units. In this study, 150 knowledge fragments were randomly selected for intercoder reliability testing. The three coders are postgraduate students and they were not told the hypothesis but were made aware of coding procedures by both oral and written instructions. Mean Cohen's Kappas for each variable by each pair of coders were

calculated. All the variables were tested with mean kappas above 0.40. It illustrates that the coding framework has good validity.

6.5 Conclusions

The experiment scheme was based on the methodology developed in chapter 5. However, the data analysis method is not possible to capture all the information from the protocol. This experiment also tried to obtain more findings about the knowledge access and utilization in product development and team decision making behavior. Results from the above experimental study can be presented in many different ways. This study focused on exploring the understanding of knowledge handling behavior of designers.

The seven factors in knowledge fragment coding framework, namely knowledge class, description, level of detail, knowledge activity, team interaction, decision activity, level of abstraction and level of aggregation, can be analyzed according to the time sequence. For each level, the operational definition for coding is described in detail. Furthermore, a deeper understanding can be obtained by combining or comparing several factors. With the understanding of these factors, knowledge handling behavior in product design will be better understood.

Chapter 7 Results of Experimental Study

7.1 Introduction

This study used the verbal protocol analysis method for data analysis (Newell & Simon, 1972). After the experiment, all the data were transcribed with time stamp. Then, the data were segmented into knowledge fragment. The knowledge fragment was defined by the coding framework. Finally, quantitative evaluations were obtained by statistical analysis. The knowledge, activities and design space can be better understood by the cognitive approach. Meanwhile, understanding of the interaction of knowledge, activities and design space can be explored. The relationships of the main results are described in Figure 7-1.

Figure 7–1 Relationships of the main results of cognitive approach to knowledge processing

As illustrated in Figure 7-1, the factors in knowledge fragments, namely knowledge class, description, level of detail, team interaction, decision making, level of abstraction and level of aggregation were analyzed respectively for answering the research objectives. Knowledge form was not discussed since this study was mainly focused on verbal protocol. Furthermore, relationships of knowledge, activity and design space were analyzed by combining or comparing several factors.

7.2 Results

7.2.1 Understanding Knowledge in Design

Three categories of knowledge were studied: knowledge class, description and level of detail.

- 1) Knowledge Class: Understanding the transfer and frequency distribution of the knowledge class.
- 2) Description: Understanding designer's concentration in design by the frequency distribution of different descriptions.
- 3) Level of Detail: Understanding the transfer and frequency of knowledge fragment between the various levels of detail.

The dynamic frequency distribution and transfer sequence were studied for each factor. Data analysis of the knowledge frequency answered three questions:

- 1) Are there differences in mean frequency between knowledge class/description/detail groups?
- 2) Does design phase influence the knowledge class/description/detail frequency? That is, does knowledge class/description/detail mean frequency change across the design phases?
- 3) Does the task influence the knowledge class/description/detail frequency? That is, does knowledge class/description/detail mean frequency change across tasks?

7.2.1.1 Knowledge class

The knowledge class frequency distribution is illustrated in the following Figure 7-2.

Figure 7-2 Knowledge class frequency distribution in design

In Figure 7-2, the HK, MK, TK and PK in the bottom level represent different knowledge classes: human knowledge, market knowledge, technology knowledge and procedural knowledge. The numbers in the middle level 1, 2 and 3 represent conceptual design, system level design and detail design respectively. The numbers in the top level 1, 2, 3, 4, 5 represent the five design teams. Shown as Figure 7-2, human knowledge was mainly referred to during the conceptual design and system level design, but was less frequent in detail design. Market knowledge was primarily referred to during the conceptual design. Technology knowledge was used in all three design phases, but more in the system design and detail design than during conceptual design. Procedural knowledge was largely used in system level design and to a lesser extent in conceptual design and detail design.

1) Multiple Comparisons

Post-hoc comparisons of the knowledge class and design phase interaction effects were performed using the Bonferroni adjustment for multiple comparisons. The mean frequency comparisons of knowledge class and design phase interaction effect are shown in Table 7-1. The C, S and D in the multiple comparisons tables represent the conceptual, system-level and detail design phase respectively. Only the mean

differences significant at the 0.05 level are listed in all multiple comparisons tables. In all multiple comparisons tables of this chapter, the values are calculated by the mean frequency of the horizontal side variable minus the mean frequency of the vertical side variable. For example, 54.8 with a minus sign in Table 7-1 represents that the mean frequency of market knowledge in system level design is visited 54.8 times less than the mean frequency of human knowledge in conceptual design.

Table 7-1 Post Hoc test of the knowledge class and design phase interaction effect on frequency (only $p < 0.05$ listed)

		Human Knowledge			Technology Knowledge			Market Knowledge			Procedural Knowledge		
		C	S	D	C	S	D	C	S	D	C	S	D
Human Knowledge	C					71.8	55.2		-54.8	-63.4	-51.0		
	S					72.0	55.4		-54.6	-63.2	-50.8		
	D				61.4	113.8	97.2						
Technology Knowledge	C					52.4			-74.2	-82.8	-70.4		-60.8
	S							-66.8	-126.6	-135.2	-122.8	-92.2	-113.2
	D							-50.2	-110.0	-118.6	-106.2	-75.6	-96.6
Market Knowledge	C								-59.8	-68.4	-56.0		
	S												
	D												
Procedural Knowledge	C												
	S												
	D												

As shown in the Table 7-1, both human knowledge and procedural knowledge did not significantly change in frequency between design phases. Technology knowledge had a significant increase from conceptual design to system level design, but there was no significant change for other paired comparisons. Market knowledge had a significant decrease from conceptual design to both of system level design and detail design. Table 7-1 also shows that technology knowledge was used most whereas procedural knowledge was used least in conceptual design. The difference equals 70.4, as shown in Table 7-1. During both system level design and detail design, technology knowledge was the most used whereas market knowledge was the least used. The difference equals 126.6 for in system level and 118.6 in detail design.

There were also significant differences in frequency between human knowledge and technology knowledge, between human knowledge and market knowledge, between

technology knowledge and market knowledge, and between technology knowledge and procedural knowledge. Table 7-1 also shows that technology knowledge was used more than any other kind of knowledge class. There were significant differences between technology knowledge and any other kind of knowledge class. This may be partly due to the fact that all subjects had engineering backgrounds. Although procedural knowledge was least used during the whole design, it was found during coding that it was very important for design teams to guide the design process.

2) Sequence Net

A sequence net can be used to describe designers' sequences in expressing, sharing, and utilizing knowledge. A knowledge class sequence net describes the designer's sequence in referring to different classes of knowledge. As illustrated in Figure 7-3, the knowledge class headed by the arrow represents the knowledge class that is expressed afterwards. The arrow circling the circle represents that the designer uses the same knowledge class consecutively. The numbers in the middle of the line represent the percentage in frequency (f) and time (t) that case happens during the design. For example, in conceptual design, the human knowledge is expressed consecutively with 15.0% in frequency and 12.3% in time. Market knowledge (MK) is expressed immediately after HK with 4.8% in frequency and 4.5% in time. Technology knowledge (TK) is expressed immediately after HK with 6.1% in frequency and 4.8% in time. Procedural knowledge is expressed immediately after HK with 1.6% in frequency and 4.4% in time. For both of frequency and time, the total percentage accumulated in each diagram is 100%. All the other data can be interpreted by similar way.

Figure 7-3 Knowledge class sequence Net in different design phases

Based on the results in Figure 7-3, some findings can be extracted.

Finding 1: In conceptual design, designers prefer consecutively expressing technology knowledge (22.2% in frequency, 18.9% in time), market knowledge (18.0% in frequency, 19.3% in time) and human knowledge (15.0% in frequency, 12.3% in time).

Finding 2: In system level design, designers prefer consecutively expressing technology knowledge (35.7% in frequency, 36.2% in time), human knowledge (13.8% in frequency, 11.9% in time) and procedural knowledge (9.4% in frequency, 11.1% in time).

Finding 3: In detail design, designers prefer consecutively expressing technology knowledge (47.3% in frequency, 51.4% in time).

Finding 4: Overall for the three design phases, designers prefer consecutively expressing technology knowledge (34.1% in frequency, 35.4% in time) and human knowledge (11.8% in frequency, 9.4% in time).

3) Profile Plots of Frequency Distribution

For each design phase, the profile plot of frequency distribution by knowledge class by task is given in Figure 7-4. The horizontal axis shows the categories of knowledge class and the vertical axis shows the frequency means. The blue and green lines represent the two different tasks: transportation device design and electronic device design. The profile plot of frequency distribution by design phase by knowledge class is also given in Figure 7-5. The horizontal axis shows the categories of design phase and the vertical axis shows the frequency means. The four different color lines represent the four different knowledge classes.

Estimated Marginal Means of frequency in total three design phases

Figure 7-4 Profile plots of frequency distribution by knowledge class by task

Figure 7–5 Profile plots of frequency distribution by design phase by knowledge class

Figure 7-4 and Figure 7-5 illustrate that knowledge class frequency distributions were little influenced by tasks in all three design phases. In comparing the frequency distributions for the two tasks, several differences emerged:

- In conceptual design, market knowledge and procedural knowledge is slightly more used for electronic device design.
- In system level design, less human and procedural knowledge but higher technology knowledge is required for transportation device design.
- In detail design, human knowledge and technology knowledge is slightly more used in transportation device design.
- For the whole three design phases, transportation device task requires higher technology knowledge but less procedural knowledge compared with electronic device task.

7.2.1.2 Description

The description frequency distribution is illustrated in Figure 7-6. Shown as Figure 7-6, cost, function, geometry, market and shape/size are largely discussed by designers. Cost and market are mainly discussed in conceptual design. Function and geometry are mainly discussed in system-level design. Shape/size is increasingly referred to from conceptual design to detail design.

1) Multiple Comparisons

Post-hoc comparisons of description and design phase interaction effects were performed using the Bonferroni adjustment for multiple comparisons. The mean frequency comparisons are shown in Table 7-2. Only the mean differences significant at the 0.05 level are listed.

Figure 7-6 Description frequency distribution in design

Table 7-2 Post Hoc test of the knowledge class and design phase interaction effect on frequency (only p<0.05 listed)

		Geometry			Material			Position			Shape			Quality			Linkage		
		C	S	D	C	S	D	C	S	D	C	S	D	C	S	D	C	S	D
Geometry	C										41.0								
	S							-28.6					-30.2						
	D										29.6								
Material	C										32.0								
	S										29.6								
	D										32.0								
Position	C										41.8								
	S										30.8								
	D										37.2								
Shape	C																		
	S												-43.4	-40.8	-36.4	-40.2	-41.0	-34.8	
	D																		
Quality	C																		
	S																		
	D																		
Linkage	C																		
	S																		
	D																		
Function	C																		
	S																		
	D																		
Kinetics	C																		
	S																		
	D																		
Assembly	C																		
	S																		
	D																		
Manufacturing	C																		
	S																		
	D																		
Ergonomics	C																		
	S																		
	D																		
Esthetics	C																		
	S																		
	D																		
Maintenance	C																		
	S																		
	D																		
Costs	C																		
	S																		
	D																		
Safety	C																		
	S																		
	D																		
Market	C																		
	S																		
	D																		
Software	C																		
	S																		
	D																		
Miscellaneous	C																		
	S																		
	D																		

Continued

		Function			Kinetics			Assembly			Manufacturing			Ergonomics			Esthetics		
		C	S	D	C	S	D	C	S	D	C	S	D	C	S	D	C	S	D
Geometry	C	34.8	37.0																
	S				-33.6	-33.0	-34.2	-35.2			-36.0	-36.0		-35.6	-35.2	-37.6	-33.8	-34.6	-36.0
	D																		
Material	C																		
	S																		
	D																		
Position	C	35.6	37.8																
	S																		
	D	31.0	33.2																
Shape	C																		
	S			-32.2	-46.8	-46.2	-47.4	-48.4	-35.4	-34.0	-49.2	-49.2	-40.4	-48.8	-48.4	-50.8	-47.0	-47.8	-49.2
	D																		
Quality	C	37.2	39.4																
	S	34.6	36.8																
	D	30.2	32.4																
Linkage	C	34.0	36.2																
	S	34.8	37.0																
	D	28.6	30.8																
Function	C				-40.6	-40.0	-41.2	-42.2	-29.2		-43.0	-43.0	-34.2	-42.6	-42.2	-44.6	-40.8	-41.6	-43.0
	S			-28.2	-42.8	-42.2	-43.4	-44.4	-31.4	-30.0	-45.2	-45.2	-36.4	-44.8	-44.4	-46.8	-43.0	-43.8	-45.2
	D																		
Kinetics	C																		
	S																		
	D																		
Assembly	C																		
	S																		
	D																		
Manufacturing	C																		
	S																		
	D																		
Ergonomics	C																		
	S																		
	D																		
Esthetics	C																		
	S																		
	D																		
Maintenance	C																		
	S																		
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Costs	C																		
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Safety	C																		
	S																		
	D																		
Market	C																		
	S																		
	D																		
Software	C																		
	S																		
	D																		
Miscellaneous	C																		
	S																		
	D																		

Continued

		Maintenance			Costs			Safety			Market			Software			Miscellaneous		
		C	S	D	C	S	D	C	S	D	C	S	D	C	S	D	C	S	D
Geometry	C										39.8								
	S	-34.4	-37.2	-36.0		-32.2	-33.8	-33.4	-35.2	-36.4			-32.8	-37.8	-33.4	-36.8			
	D										28.4								
Material	C										30.8								
	S										28.4								
	D										30.8								
Position	C				28.4						40.6								
	S										29.6								
	D										36.0								
Shape	C																		
	S	-47.6	-50.4	-49.2		-45.4	-47.0	-46.6	-48.4	-49.6		-40.6	-46.0	-51.0	-46.6	-50.0	-34.8		-39.2
	D																		
Quality	C				30.0						42.2								
	S										39.6								
	D										35.2								
Linkage	C										39.0								
	S										39.8								
	D										33.6								
Function	C	-41.4	-44.2	-43.0		-39.2	-40.8	-40.4	-42.2	-43.4		-34.4	-39.8	-44.8	-40.4	-43.8	-28.6		-33.0
	S	-43.6	-46.4	-45.2		-41.4	-43.0	-42.6	-44.4	-45.6		-36.6	-42.0	-47.0	-42.6	-46.0	-30.8		-35.2
	D										31.0								
Kinetics	C				33.4						45.6								
	S				32.8						45.0								
	D				34.0						46.2								
Assembly	C				35.0						47.2								
	S										34.2								
	D										32.8								
Manufacturing	C				35.8						48.0								
	S				35.8						48.0								
	D										39.2								
Ergonomics	C				35.4						47.6								
	S				35.0						47.2								
	D				37.4						49.6								
Esthetics	C				33.6						45.8								
	S				34.4						46.6								
	D				35.8						48.0								
Maintenance	C				34.2						46.4								
	S				37.0						49.2								
	D				35.8						48.0								
Costs	C					-32.0	-33.6	-33.2	-35.0	-36.2			-32.6	-37.6	-33.2	-36.6			
	S										44.2								
	D										45.8								
Safety	C										45.4								
	S										47.2								
	D										48.4								
Market	C											-39.4	-44.8	-49.8	-45.4	-48.8	-33.6		-38.0
	S																		
	D																		
Software	C																		
	S																		
	D																		
Miscellaneous	C																		
	S																		
	D																		

As shown in the Table 7-2, only function, costs and market significantly change in frequency between design phases. Function decreased significantly from system level design to detail design. Both cost and market decreased significantly from conceptual design to system design and detail design. The results show that all other kinds of descriptions did not change significantly between design phases.

Table 7-2 also shows that market, function and cost were most referred to, whereas software, manufacturing, ergonomics, assembly, maintenance, esthetics, safety were least referred in conceptual design (difference more than 45.0 compared with market, as shown in Table 7-2). In system level design, shape, geometry and function were most referred to, whereas maintenance, manufacturing, safety, ergonomics, esthetics, software, kinetics and costs were least referred to (difference more than 45.0 compared with shape, as shown in Table 7-2). There was no significant difference between any kinds of descriptions during detail design.

2) Profile Plots of Frequency Distribution

For each design phase, the profile plot of frequency distribution by description by task is given in Figure 7-7.

Figure 7-7 Profile plots of frequency distribution by description by task

In Figure 7-7, the horizontal axis shows the categories of description and the vertical axis shows the frequency means. The blue and green lines represent the two different tasks: transportation device design and electronic device design. Figure 7-7 illustrates that most description frequency distributions were marginally affected by the two tasks. In comparing the frequency distributions for the two tasks, several differences emerged:

- In conceptual design, it is found that function is largely more referred to in electronic device design than in transportation device design. Geometry, material, position and shape are slightly more referred to in transportation device design.
- In system level design, position and assembly are more referred to in transportation device design, but material and software are more referred to in electronic device design.
- In detail design, geometry, position, shape, assembly and manufacturing are much more referred to in transportation device design, whereas material and quality are more referred to in electronic device design.
- For the whole three design phases, transportation device design visited more in shape and assembly but less in function, software and quality compared with electronic device design.

7.2.1.3 Level of Detail

The level of detail frequency distribution is illustrated in Figure 7-8.

Figure 7-8 Level of detail frequency distribution in design

1) Multiple Comparisons

Post-hoc comparisons of the level of detail and design phase interaction effects were performed using the Bonferroni adjustment for multiple comparisons. The mean frequency comparisons are shown in Table 7-3. Only the mean differences significant at the 0.05 level are listed.

Table 7-3 Post Hoc test of level of detail and design phase interaction effect on frequency (only $p < 0.05$ listed)

		Unlabeled			Labeled			Associative			Qualitative			Quantitative		
		C	S	D	C	S	D	C	S	D	C	S	D	C	S	D
Unlabeled	C				70.4	98.2	61.8				63.4					
	S				66.6	94.4										
	D				78.0	105.8	69.4				71.0					
Labeled	C							-65.2		-69.8						
	S							-93.0	-84.4	-97.6		-62.0			-76.2	
	D									-61.2						
Associative	C															
	S															
	D										62.8					
Qualitative	C															
	S															
	D															
Quantitative	C															
	S															
	D															

As shown in the Table 7-3, all the levels of detail did not change significantly in frequency between design phases. This implies that the designer's communication behavior in expressing knowledge was not much influenced by design phases. However, the results show that there were significant differences in frequency between unlabeled and labeled, and between labeled and associative. Both the qualitative and quantitative levels did not produce many significant differences with other levels of detail.

Table 7-3 also shows that the labeled level was the most used whereas the unlabeled was the least used in all three design phases (difference = 70.4 in conceptual design, 94.4 in system design, and 69.4 in detail design as shown in Table 7-3). It was also found that qualitative level was largely visited only in conceptual design. Associative level was little visited in all three design phases. The results show that labeled level was used more than any other level of detail. This may be partly due to the fact that most of the subjects had an extensive experience in design, and thus they expressed their ideas with label rather than unlabeled level. Although qualitative and quantitative levels produced no significant results, it was found during coding that they are very important for the detail discussion in detail design.

2) Sequence Net

In Figure 7-9, the sequence net describes designers' sequences in using different level of detail in expressing knowledge.

Figure 7-9 Level of detail sequence Net in different design phases

Based on the results in Figure 7-9, some findings can be extracted.

Finding 5: In conceptual design, designers prefer consecutively expressing knowledge in labeled level (17.4% in frequency, 15.4% in time) and qualitative level (14.1% in frequency, 15.1% in time). That is, designers prefer expressing the knowledge in labeled level again after they have visited the label level. They also prefer visiting the qualitative level after they have visited the qualitative level.

Finding 6: In system level design, designers prefer consecutively expressing knowledge in labeled level (22.6% in frequency, 21.4% in time) and quantitative level (11.9% in frequency, 11.5% in time).

Finding 7: In detail design, designers prefer consecutively expressing knowledge in labeled level (23.1% in frequency, 22.6% in time), qualitative level (11.4% in frequency, 12.3% in time) and quantitative level (10.0% in frequency, 12.6% in time).

Finding 8: Overall for the three design phases, designers prefer consecutively expressing knowledge in labeled level (20.9% in frequency, 19.8% in time), qualitative level (10.8% in frequency, 11.1% in time) and quantitative level (10.6% in frequency, 10.9% in time).

3) Profile Plots of Frequency Distribution

In Figure 7-10, for each design phase, the profile plot of frequency distribution by level of detail by task is given.

Figure 7–10 Profile plots of frequency distribution by level of detail by task

In Figure 7-10, the horizontal axis shows the categories of level of detail and the vertical axis shows the frequency means. The blue and green lines represent the two different tasks: transportation device design and electronic device design. In comparing the frequency distributions for the two tasks, several differences emerged:

- In conceptual design, the qualitative level is more visited but labeled and associative levels are less visited in transportation device design.
- In system level design, the quantitative are more visited but unlabeled and labeled are less visited in transportation device design.
- In detail design, associative, the qualitative and quantitative levels are more visited in transportation device design.
- For the whole three design phases, the transportation device design requires higher visit in qualitative and quantitative but less visit in labeled level compared with electronic device task.

7.2.2 Understanding the Activities in Design

For the design teams, three activities were studied:

- 1) Knowledge activity: Understanding the transfer and frequency distribution of the knowledge activities.
- 2) Team interaction: Understanding the transfer and frequency distribution of different team interaction modes.
- 3) Decision activity: Understanding the transfer and frequency distribution of different decision activities.

The dynamic frequency distribution and transfer sequence were studied for each factor. The activity frequencies were analyzed to answer three questions:

- 1) Are there differences in mean frequency between knowledge activity/team interaction mode/decision making activity groups?
- 2) Does the design phase influence the knowledge activity/team interaction mode/decision making activity frequency? That is, does knowledge activity/team interaction mode/decision making activity mean frequency change across the design phases?
- 3) Does the task influence the knowledge activity/team interaction mode/decision making activity frequency? That is, does knowledge activity/team interaction mode/decision making activity mean frequency change across tasks?

7.2.2.1 Knowledge Activity

Knowledge activity frequency distribution is illustrated in Figure 7-11.

Figure 7-11 Knowledge activity frequency distribution in design

1) Multiple Comparisons

Post-hoc comparisons of the knowledge activity and design phase interaction effects were performed using the Bonferroni adjustment for multiple comparisons. The mean frequency comparisons are shown in Table 7-4. Only the mean differences significant at the 0.05 level are listed.

Table 7-4 Post Hoc test of the knowledge activity and design phase interaction effect on frequency (only $p < 0.05$ listed)

		Knowledge Generation			Knowledge Sharing			Knowledge Evaluation			Knowledge Utilization		
		C	S	D	C	S	D	C	S	D	C	S	D
Knowledge Generation	C												
	S												
	D					51.6		60.8	47.8				
Knowledge Sharing	C												
	S												
	D												
Knowledge Evaluation	C												-48.8
	S												
	D												
Knowledge Utilization	C												
	S												
	D												

As shown in the Table 7-4, knowledge activities did not change significantly in frequency between design phases. The results also show that there were no significant differences in frequency between different knowledge activities in the same design phase.

2) Sequence Net

Knowledge activity sequence net describes designers' sequences in using different kinds of knowledge activity in expressing knowledge, as illustrated in Figure 7-12.

Figure 7-12 Knowledge activity sequence Net in different design phases

Based on the results in Figure 7-12, some findings can be extracted.

Finding 9: In conceptual design, designers prefer consecutive knowledge evaluation (13.0% in frequency, 13.0% in time) and knowledge sharing (9.7% in frequency, 10.2% in time).

Finding 10: In system level design, designers prefer consecutive knowledge sharing (13.1% in frequency, 16.6% in time).

Finding 11: In detail design, designers prefer consecutive knowledge sharing (13.5% in frequency, 16.9% in time).

Finding 12: Overall for the three design phases, designers prefer consecutive knowledge sharing (12.0% in frequency, 14.6% in time).

3) Profile Plots of Frequency Distribution

For each design phase, the profile plot of frequency distribution by knowledge activity by task is given in Figure 7-13. In Figure 7-13, the horizontal axis shows the categories of knowledge activity and the vertical axis shows the frequency means. The blue and green lines represent the two different tasks: transportation device design and electronic device design. In comparing the frequency distributions for the two tasks, several differences emerged:

- In conceptual design, knowledge sharing, evaluation and utilization are more visited in electronic device design.
- In system level design, knowledge generation, sharing and evaluation are more visited in electronic device design.
- In detail design, all the knowledge activities are more visited in transportation device design.
- For the whole three design phases, transportation device design has similar knowledge activity frequency distribution with electronic device design.

Figure 7-13 Profile plots of frequency distribution by knowledge activity by task

7.2.2.2 Team Interaction

The team interaction mode frequency distribution is illustrated in Figure 7-14.

Figure 7-14 Team interaction mode frequency distribution in design

1) Multiple Comparisons

Post-hoc comparisons of the knowledge activity and design phase interaction effects were performed using the Bonferroni adjustment for multiple comparisons. The mean frequency comparisons are shown in Table 7-5. Only the mean differences significant at the 0.05 level are listed.

Table 7-5 Post Hoc test of the team interaction mode and design phase interaction effect on frequency (only $p < 0.05$ listed)

		1-Way			2-Way			3-Way			4-Way		
		C	S	D	C	S	D	C	S	D	C	S	D
1-Way	C												
	S												
	D												
2-Way	C												-92.2
	S										-95.4	-96.4	-111.4
	D										-83.0	-98.0	
3-Way	C												
	S												
	D												
4-Way	C												
	S												
	D												

As shown in the Table 7-5, team interaction modes do not change significantly in frequency between design phases. There were significant differences between 2-way interaction and 4-way interaction. The results show that 2-way communication was used most during the whole design process. Table 7-5 also shows that there was no significant difference between all the team interaction modes in conceptual design. In both system level design and detail design, 2-way was the most used whereas 4-way was the least used (difference = 96.4 in system design, and 98.4 in detail design as shown in Table 7-5).

2) Sequence Net

Team interaction mode sequence net describes designers' sequences in using different interaction mode in communication, as illustrated in Figure 7-15.

Conceptual design

System level design

Detail design

Total design

Figure 7-15 Team interaction mode sequence Net in different design phases

Based on the results in Figure 7-15, some findings can be extracted.

Finding 13: In conceptual design, designers prefer consecutive 2-way communication (15.1% in frequency, 14.8% in time), 1-way communication (11.4% in frequency, 14.8% in time), and 3-way communication (11.2% in frequency, 9.7% in time). Designer also prefers 2-way followed by 3-way communication (11.3% in frequency, 9.5% in time), and 3-way followed by 2-way communication (10.3% in frequency, 11.1% in time).

Finding 14: In system level design, designers prefer consecutive 2-way communication (19.2% in frequency, 18.4% in time) and 3-way communication (10.6% in frequency, 11.8% in time). Designer also prefers 2-way followed by 3-way communication (11.4% in frequency, 9.8% in time), 3-way followed by 2-way communication (11.1% in frequency, 11.5% in time), and 2-way followed by 1-way communication (8.5% in frequency, 10.3% in time).

Finding 15: In detail design, designers prefer consecutive 2-way communication (29.1% in frequency, 24.8% in time) and 1-way communication (14.2% in frequency, 14.3% in time). Designer also prefers 1-way followed by 2-way communication (10.4% in frequency, 8.7% in time), 3-way followed by 2-way communication (10.3% in frequency, 11.1% in time), and 2-way followed by 3-way communication (9.6% in frequency, 10.4% in time).

Finding 16: Overall for the three design phases, designers prefer consecutive 2-way communication (20.4% in frequency, 18.9% in time) and 1-way communication (11.0% in frequency, 12.2% in time). Designer also prefers 2-way followed by 3-way communication (10.9% in frequency, 10.0% in time), 3-way followed by 2-way communication (10.7% in frequency, 11.0% in time), and 2-way followed by 1-way communication (9.2% in frequency, 10.8% in time).

3) Profile Plots of Frequency Distribution

For each design phase, the profile plot of frequency distribution by team interaction by task is given in Figure 7-16. In Figure 7-16, the horizontal axis shows the categories of knowledge activity and the vertical axis shows the frequency means. The

blue and green lines represent the two different tasks: transportation device design and electronic device design. In comparing the frequency distributions for the two tasks, several differences emerged:

- In conceptual design, 2-way and 3-way communication are more used in electronic device design than in transportation device design.
- In system level design, both tasks have similar team interaction mode frequency distribution.
- In detail design, 2-way and 3-way communication are more used but 1-way is less used in transportation device design.
- For the whole three design phases, transportation device design has similar frequency distribution with electronic device design.

Figure 7-16 Profile plots of frequency distribution by team interaction by task

7.2.2.3 Decision Making Activity

The decision activity frequency distribution is illustrated in Figure 7-17.

Figure 7-17 Decision making activity frequency distribution in design

1) Multiple Comparisons

Post-hoc comparisons of the decision activity and design phase interaction effects were performed using the Bonferroni adjustment for multiple comparisons. The mean frequency comparisons are shown in Table 7-6. Only the mean differences significant at the 0.05 level are listed.

Table 7-6 Post Hoc test of decision making activity and design phase interaction effect on frequency (only $p < 0.05$ listed)

		Objective			Alternative			Criterion			Decision			Outcome		
		C	S	D	C	S	D	C	S	D	C	S	D	C	S	D
Objective	C					49.8										
	S															
	D					54.6										
Alternative	C										-46.0		-56.4	-46.6	-54.0	-57.4
	S									-54.0	-63.4	-50.8	-73.8	-64.0	-71.4	-74.8
	D												-52.0		-49.6	-53.0
Criterion	C												-54.6		-52.2	-55.6
	S															
	D															
Decision	C															
	S															
	D															
Outcome	C															
	S															
	D															

As shown in the Table 7-6, all decision activities do not have significant change in frequency between design phases. It implies that the designer's decision making behavior was not much influenced by design phases. Table 7-6 also shows that alternatives were generated more than any other decision making activity. Designers generated a lot of alternatives, but they made few decisions. The data also show that designers did not evaluate the outcome for each alternative. Only a few of the alternatives were further assessed by designers.

The results show that there are significant differences in frequency between alternative and outcome, and between alternative and decision. The results show that alternative was the most visited whereas outcome was the least visited in all three design phases (difference = 46.6 in conceptual design, 71.4 in system design, and 53.0 in detail design as shown in Table 7-6). There are also significant differences between alternative and decision in all three design phases (difference = 46.0 in conceptual design, 50.8 in system design, and 52.0 in detail design as shown in Table 7-6).

2) Sequence Net

Decision making activity sequence net describes designers' sequences in visiting different levels of decision activity, as illustrated in Figure 7-18. Based on the results in Figure 7-18, some findings can be extracted.

Finding 17: In conceptual design, designers prefer consecutively quoting criteria (13.8% in frequency, 12.6% in time) and generating alternative (10.3% in frequency, 8.0% in time).

Finding 18: In system level design, designers prefer consecutively generating alternative (13.1% in frequency, 12.4% in time).

Finding 19: In detail design, designers prefer consecutively generating alternative (17.1% in frequency, 15.4% in time). Designer also prefers identifying objective followed by generating alternative (10.0% in frequency, 10.2% in time).

Finding 20: Overall for the three design phases, designers prefer consecutively generating alternative (13.2% in frequency, 11.9% in time).

Conceptual design

System level design

Detail design

Total design

Figure 7-18 Decision activities sequence Net in different design phases

3) Profile Plots of Frequency Distribution

For each design phase, the profile plot of frequency distribution by decision making activity by task is given in Figure 7-19. In Figure 7-19, the horizontal axis shows the categories of decision making activity and the vertical axis shows the frequency means. The blue and green lines represent the two different tasks: transportation device design and electronic device design. In comparing the frequency distributions for the two tasks, several differences emerged:

- In conceptual design, more alternatives are generated and more decisions are made in electronic device design.
- In system level design, objective and decision are more visited but alternative and criterion are less visited in electronic device design.
- In detail design, all decision making activities are more involved in transportation device design.
- For the whole three design phases, more alternatives are generated but fewer decisions are made in transportation device design.

Figure 7-19 Profile plots of frequency distribution by decision making activity by task

7.2.3 Understanding the Design Space

Level of abstraction and level of aggregation were studied for understanding the design space:

- 1) Level of Abstraction: Understanding the transfer and frequency distribution of different levels of abstraction during design.
- 2) Level of Aggregation: Understanding the transfer and frequency distribution of different levels of the aggregation during design.

The dynamic frequency distribution and transfer sequence were studied for each factor. The design space frequencies were analyzed to answer three questions:

- 1) Are there differences in mean frequency between abstraction/aggregation level groups?
- 2) Does the design phase influence the abstraction/aggregation level frequency? That is, does abstraction/aggregation level mean frequency change across the design phases?
- 3) Does the task influence the abstraction/aggregation level frequency? That is, does abstraction/aggregation level mean frequency change across tasks?

7.2.3.1 Level of Abstraction

The level of abstraction frequency distribution is illustrated in Figure 7-20.

Figure 7–20 Level of abstraction frequency distribution in design

1) Multiple Comparisons

Post-hoc comparisons of the level of abstraction and design phase interaction effects were performed using the Bonferroni adjustment for multiple comparisons. The mean frequency comparisons are shown in Table 7-7. Only the mean differences significant at the 0.05 level are listed.

Table 7-7 Post Hoc test of level of abstraction and design phase interaction effect on frequency (only $p < 0.05$ listed)

		Purpose			Abstract Function			Generalized Function			Physical Function			Physical Form		
		C	S	D	C	S	D	C	S	D	C	S	D	C	S	D
Purpose	C		-67.8	-83.8	-110.4	-102.4	-113.6	-66.4			-90.4	-85.2	-108.4	-94.6	-68.0	-97.6
	S								52.2							
	D								68.2	60.2						
Abstract Function	C								94.8	86.8						
	S								86.8	78.8						
	D								98.0	90.0						
Generalized Function	C								50.8							
	S										-74.8	-69.6	-92.8	-79.0	-52.4	-82.0
	D										-66.8	-61.6	-84.8	-71.0		-74.0
Physical Function	C															
	S															
	D															
Physical Form	C															
	S															
	D															

As shown in the Table 7-7, in purpose level, there was a significant decrease in frequency from conceptual design to system design as well as from system design to detail design. For generalized function, there was a significant increase from conceptual design to system design. For other levels of abstraction, there was no significant change between design phases.

Table 7-7 also shows that the purpose was the most visited whereas abstract function was the least visited in conceptual design (difference equal to 110.4). In both system level design and detail design, generalized function was the most visited whereas abstract function was the least visited (difference=86.8 in system level design, 90.0 in detail design). The results also show that there were significant differences in frequency between purpose and all any other level of abstraction in conceptual design. In both system level design and detail design, there were also significant differences between generalized function and any other level of abstraction.

2) Sequence Net

Level of abstraction sequence net describes designers' sequences in visiting different levels of abstraction in design space, as illustrated in Figure 7-21. Based on the results in Figure 7-21, some findings can be extracted.

Finding 21: In conceptual design, designers prefer consecutively visiting purpose level (34.8% in frequency, 40.2% in time) and generalized function level (12.8% in frequency, 11.1% in time).

Finding 22: In system level design, designers prefer consecutively visiting generalized function level (25.9% in frequency, 25.2% in time), physical form level (12.2% in frequency, 12.7% in time) and purpose level (9.9% in frequency, 10.7% in time).

Finding 23: In detail design, designers prefer consecutively visiting generalized function level (37.2% in frequency, 37.0% in time) and purpose level (11.7% in frequency, 12.5% in time).

Finding 24: Overall for the three design phases, designers prefer consecutively visiting generalized function level (24.4% in frequency, 24.4% in time) and purpose level (19.1% in frequency, 21.2% in time).

Figure 7-21 Level of abstraction sequence Net in different design phases

3) Profile Plots of Frequency Distribution

For each design phase, the profile plot of frequency distribution by abstraction level by task is given in Figure 7-22. In Figure 7-22, the horizontal axis shows the categories of abstraction level and the vertical axis shows the frequency means. The blue and green lines represent the two different tasks: transportation device design and electronic device design. In comparing the frequency distributions for the two tasks, several differences emerged:

- In conceptual design, the generalized function is more visited in transportation device design. Physical function and purpose are more visited in electronic device design.
- In system level design, the generalized function is more visited but the purpose is less visited in transportation device design.
- In detail design, generalized function and physical form are more visited in transportation device design. Abstract function and purpose are more visited in electronic device design.
- For the whole three design phases, generalized function and physical form are more visited in transportation device design. The purpose, abstract function and physical function are more visited in electronic device design.

Figure 7–22 Profile plots of frequency distribution by abstraction level by task

7.2.3.2 Level of Aggregation

The level of aggregation frequency distribution is illustrated in Figure 7-23.

Figure 7–23 Level of aggregation frequency distribution in three design phases

1) Multiple Comparisons

Post-hoc comparisons of the level of aggregation effects in each design phase were performed using the Bonferroni adjustment for multiple comparisons. The mean frequency comparisons in conceptual design are shown in Table 7-8. Only the mean differences significant at the 0.05 level are listed.

Table 7-8 Post Hoc test of level of aggregation effect on frequency in conceptual design (only $p < 0.05$ listed)

	Customer Needs Identification	Concept Generation	Concept Evaluation	Concept Selection	Concept Refinement	Remaining Design Planning
Customer Needs Identification			44.8			
Concept Generation						
Concept Evaluation				-59.0		-64.6
Concept Selection						
Concept Refinement						-40.6
Remaining Design Planning						

As shown in the Table 7-8, there was a significant difference in frequency between customer needs identification and concept evaluation. In concept evaluation level, there were significant differences in frequency compared with concept selection and remaining design planning. There was also a significant difference in frequency between concept refinement and remaining design planning. There was no significant difference between concept generation and any other level of aggregation in conceptual design. Table 7-8 also shows concept evaluation was visited the most times among all levels of aggregation. Designers evaluated much before selecting any concept. Remaining design planning level was visited least, but it is found very important for guiding the design process during verbal analysis.

The mean frequency comparisons in system-level design are shown in Table 7-9.

Table 7-9 Post Hoc test of level of aggregation effect on frequency in system-level design (only $p < 0.05$ listed)

	Component	Assembly	Function Unit	Subsystem	Whole System
Component			41.6		
Assembly					
Function Unit				-41.2	
Subsystem					
Whole System					

As shown in the Table 7-9, there was a significant difference in frequency between component and function unit, and between function unit and subsystem. Function unit was visited the most times among all levels of aggregation, whereas component was visited with the fewest times. There was no significant difference among other levels of aggregation in system level design.

The mean frequency comparisons in detail design are shown in Table 7-10.

Table 7-10 Post Hoc test of level of aggregation effect on frequency in detail design (only $p < 0.05$ listed)

	Objective Structuring	Preliminary Design	Refinement	Detail Action
Objective Structuring				
Preliminary Design				25.0
Refinement				
Detail Action				

As shown in the Table 7-10, there was only one significant difference in frequency between preliminary design and detail action. The results show that detail action level was visited the most times, whereas preliminary design level was visited with the fewest times. The results imply that it is necessary to use experienced designers as subjects. Otherwise, it will be quite difficult for novice designers to go into detail action level in design. There was no significant difference among other levels of aggregation in detail design.

2) Sequence Net

Level of aggregation sequence net describes designers' sequences in visiting different levels of aggregation in design space, as illustrated in Figure 7-24. Based on the results in Figure 7-24, some findings can be extracted.

Finding 25: In conceptual design, designers prefer consecutively evaluating concept (12.2% in frequency, 10.9% in time).

Finding 26: In system level design, designers prefer consecutively visiting the function unit level (17.9% in frequency, 14.9% in time), whole system level (16.5% in frequency, 19.3% in time) and assembly level (15.8% in frequency, 15.0% in time).

Finding 27: In detail design, designers prefer consecutively visiting detail action level (16.2% in frequency, 17.1% in time), objective structuring (12.9% in frequency, 13.4% in time), and refinement (10.0% in frequency, 7.9% in time).

Figure 7-24 Level of aggregation sequence Net in different design phases

3) Profile Plots of Frequency Distribution

For each design phase, the profile plot of frequency distribution by aggregation level by task is given in Figure 7-25. In Figure 7-25, the horizontal axis shows the categories of aggregation level and the vertical axis shows the frequency means. The blue and green lines represent the two different tasks: transportation device design and electronic device design. In comparing the frequency distributions for the two tasks, several differences emerged:

- In conceptual design, concept is more evaluated but less refined in transportation device design. Remaining design is more planned in electronic device design.
- In system level design, assembly and function unit are more visited in transportation device design. Component, subsystem and whole system are more discussed in electronic device design.
- In detail design, all levels of aggregation are more visited in transportation device design than in electronic device design.

Figure 7–25 Profile plots of frequency distribution by aggregation level by task

7.2.4 Understanding the Relationships of Knowledge, Activities and Design Space

7.2.4.1 Understanding the Relationships among Different Factors of Knowledge, Activity and Design Space

1) Understanding the Relationships among Different Factors of Knowledge

The relationships among knowledge class, description and level of detail are illustrated in Figure 7-26 and Figure 7-27.

Based on the results in Figure 7-26 and Figure 7-27, some findings can be extracted.

Finding 28: Human knowledge is used mostly in describing the function and shape/size in design. It is commonly expressed in label level for function description and qualitative level for shape/size.

Finding 29: Market knowledge is used mostly in describing the cost and market in design. It is commonly expressed in quantitative and qualitative levels in describing the cost, whereas in qualitative and label levels in describing the market.

Finding 30: Procedural knowledge is used mostly in describing miscellaneous and assemblage in design. It is commonly expressed in various levels in describing the miscellaneous, whereas in label levels in describing the assemblage.

Finding 31: Technology knowledge is the most used in design; it is used mostly in describing function, shape/size, material and geometry. It is commonly expressed in label level in describing the function, quantitative level in describing shape/size, label and quantitative levels in describing material, and qualitative and quantitative levels in describing geometry.

Figure 7-26 The frequency relationships among knowledge class, description and level of detail

Figure 7-27 The time relationships among knowledge class, description and level of detail

2) Understanding the Relationships among Different Factors of Activity

The relationships among knowledge class, description and level of detail are illustrated in Figure 7-28.

Figure 7–28 The frequency and time relationships among knowledge activity, team interaction mode and decision activity

Based on the results in Figure 7-28, some findings can be extracted.

Finding 32: Knowledge generation is mostly related with 1-way or 2-way communication. It is commonly related with generating alternative and identifying objective in decision making.

Finding 33: Knowledge sharing is mostly related with 2-way or 3-way communication. It is commonly related with objective, alternative and criteria in decision making, whereas seldom related with decision and outcome.

Finding 34: Knowledge evaluation is mostly related with 2-way or 3-way communication. It is commonly related with criteria and outcome in decision making.

Finding 35: Knowledge utilization is mostly related with 2-way or 1-way communication. It is commonly related with making decision, generating alternative in decision making.

3) Understanding the Relationships among Different Factors of Design Space

The relationships among level of abstraction and level of aggregation in conceptual design are illustrated in Figure 7-29.

Figure 7–29 The frequency and time relationships among level of abstraction and level of aggregation in conceptual design

Based on the results in Figure 7-29, some findings can be extracted.

Finding 36: In conceptual design, the purpose level is the most visited. It is mostly related with customer needs identification and concept evaluation.

Finding 37: In conceptual design, abstract Function is the least visited. It is mostly related with concept evaluation and concept refinement.

Finding 38: In conceptual design, the generalized function is mostly related with concept generation, concept evaluation and concept refinement.

Finding 39: In conceptual design, physical function is mostly related with concept generation, concept evaluation and concept refinement.

Finding 40: In conceptual design, physical form is mostly related with concept evaluation and concept refinement.

The relationships among level of abstraction and level of aggregation in system level design are illustrated in Figure 7-30.

Figure 7-30 The frequency and time relationships among level of abstraction and level of aggregation in system level design

Based on the results in Figure 7-30, some findings can be extracted.

Finding 41: In system level design, the purpose level is mostly related with whole system level of aggregation.

Finding 42: In system level design, abstract Function is the least visited. It is mostly related with function unit level of aggregation.

Finding 43: In system level design, the generalized function is the most visited. It is mostly related with assembly level of aggregation.

Finding 44: In system level design, physical function is mostly related with function unit.

Finding 45: In system level design, physical form is mostly related with whole system level of aggregation.

The relationships among level of abstraction and level of aggregation in detail design are illustrated in Figure 7-31.

Figure 7–31 The frequency and time relationships among level of abstraction and level of aggregation in detail design

Based on the results in Figure 7-31, some findings can be extracted.

Finding 46: In detail design, the purpose level is mostly related with objective structuring.

Finding 47: In detail design, abstract Function is the least visited. It is mostly related with detail action level of aggregation.

Finding 48: In detail design, the generalized function is most visited. It is mostly related with detail action and refinement level in design.

Finding 49: In detail design, physical function is mostly related with objective structuring and primary design.

Finding 50: In detail design, physical form is mostly related with refinement and detail action.

7.2.4.2 Understanding the Interactive Relationships among Knowledge, Activity and Design Space

1) Understanding the Interactive Relationships between Knowledge and Activity

The interactive relationships between knowledge and activity are illustrated in Figure 7-32.

Figure 7–32 The frequency and time relationships among knowledge class, knowledge activity and decision making

Based on the results in Figure 7-32, some findings can be extracted.

Finding 51: Knowledge generation is mostly related with human knowledge and technology knowledge. The knowledge generated is commonly used for generating alternative in decision making.

Finding 52: Knowledge sharing is mostly related with technology knowledge. Designers share their technology knowledge for identifying objective, generating alternative and quoting criteria.

Finding 53: Knowledge evaluation is mostly related with technology knowledge. Designers commonly use the technology knowledge as criteria for knowledge evaluation.

Finding 54: Knowledge utilization is mostly related with technology knowledge and procedure knowledge. The knowledge is commonly used for generating

alternatives and making decisions.

2) Understanding the Interactive Relationships between Knowledge and Design Space

The interactive relationships between knowledge and conceptual design space are illustrated in Figure 7-33.

Figure 7–33 The frequency and time relationships between knowledge and conceptual design space

Based on the results in Figure 7-33, some findings can be extracted.

Finding 55: In conceptual design, the purpose level is mostly related with market knowledge. The knowledge is used mostly for customer needs identification and concept evaluation.

Finding 56: In conceptual design, abstract Function is mostly related with technology knowledge. The knowledge is commonly used for concept evaluation and concept refinement.

Finding 57: In conceptual design, the generalized function is mostly related technology knowledge. The knowledge is commonly used for concept generation, concept evaluation and concept refinement.

Finding 58: In conceptual design, physical function is mostly related with human knowledge and technology knowledge. The knowledge is commonly used for concept generation and concept evaluation.

Finding 59: In conceptual design, physical form is mostly related with human

knowledge and technology knowledge. The knowledge is mainly used for concept evaluation.

The interactive relationships between knowledge and system level design space are illustrated in Figure 7-34.

Figure 7–34 The frequency and time relationships between knowledge and system level design space

Based on the results in Figure 7-34, some findings can be extracted.

Finding 60: In system level design, designer mainly uses procedural knowledge in purpose level for whole system design.

Finding 61: In system level design, designer mainly uses technology knowledge in abstract Function level for function unit design.

Finding 62: In system level design, designer mainly uses technology knowledge in generalized function level for assembly design.

Finding 63: In system level design, designer mainly uses technology knowledge in physical function level for function unit design.

Finding 64: In system level design, designer mainly uses human knowledge and technology knowledge in physical form level for whole system design.

The interactive relationships between knowledge and detail design space are illustrated in Figure 7-35.

Figure 7-35 The frequency and time relationships among knowledge and detail design space

Based on the results in Figure 7-35, some findings can be extracted.

Finding 65: In detail design, designer mainly uses procedural knowledge in purpose level for objective structuring.

Finding 66: In detail design, designer mainly uses technology knowledge in abstract function level for detail action in design.

Finding 67: In detail design, designer mainly uses technology knowledge in generalized function level for detail action, refinement and preliminary design.

Finding 68: In detail design, designer mainly uses technology knowledge in physical function level for objective structuring and preliminary design.

Finding 69: In detail design, designer mainly uses technology knowledge in physical form level for detail action and refinement.

3) Understanding the Interactive Relationships between Knowledge Activity and Design Space

The interactive relationships between knowledge activity and conceptual design space are illustrated in Figure 7-36.

Figure 7-36 The frequency and time relationships among knowledge activity and conceptual design space

Based on the results in Figure 7-36, some findings can be extracted.

Finding 70: In conceptual design, the designer is involved in different kinds of knowledge activity in purpose level. Knowledge sharing and evaluation are mainly involved in concept evaluation and customer needs identification.

Finding 71: In conceptual design, knowledge sharing is mainly involved in concept evaluation and refinement in abstract function level.

Finding 72: In conceptual design, different kinds of knowledge activity are almost equally involved in generalized function level. Knowledge generation and evaluation are mainly involved in concept generation and evaluation.

Finding 73: In conceptual design, knowledge generation and evaluation are mainly involved in concept generation and evaluation in physical function level.

Finding 74: In conceptual design, knowledge evaluation is mainly involved in concept evaluation in physical form level.

The interactive relationships between knowledge activity and system level design space are illustrated in Figure 7-37.

Figure 7–37 The frequency and time relationships among knowledge activity and system level design space

Based on the results in Figure 7-37, some findings can be extracted.

Finding 75: In system level design, knowledge sharing and evaluation are mainly involved in assembly design in purpose level.

Finding 76: In system level design, knowledge sharing and evaluation are mainly involved in function unit design in abstract function level.

Finding 77: In system level design, all four kinds of knowledge activity are largely involved in generalized function level. The four kinds of knowledge activity are mainly involved in assembly design.

Finding 78: In system level design, the four kinds of knowledge activity are mainly involved in function unit design in physical function level.

Finding 79: In system level design, the four kinds of knowledge activity are mainly involved in whole system design in physical form level.

The interactive relationships between knowledge activity and detail design space are illustrated in Figure 7-38.

Figure 7–38 The frequency and time relationships among knowledge activity and detail design space

Based on the results in Figure 7-38, some findings can be extracted.

Finding 80: In detail design, all kinds of knowledge activity are mainly involved in objective structuring in purpose level.

Finding 81: In detail design, knowledge sharing is mainly involved in detail action in abstract function level.

Finding 82: In detail design, all four kinds of knowledge activity are largely involved in generalized function level. Knowledge sharing, evaluation and utilization are mainly involved in detail action, whereas knowledge generation is mainly involved in preliminary design.

Finding 83: In detail design, all kinds of knowledge activity are mainly involved in objective structuring and preliminary design in physical function level.

Finding 84: In detail design, knowledge evaluation is mainly involved in refinement in physical form level.

7.3 Conclusions

In this study a total of 8 hypotheses were tested and 84 findings were presented. The results are organized as shown in Figure 7-39. Main findings from the experimental study were summarized in Table 7-11.

Figure 7-39 results distribution in the study

The results provide the understanding of the content, action and context of knowledge in product design. The results also provide the answers to what knowledge is used, how the knowledge is communicated, and how the knowledge is integrated into design space in different design phases. The results provide the understanding on how the knowledge is shared in a team and how the knowledge is utilized for decision making in product design. All the findings will provide a rich insight for ICT support for product design. The theoretical implications for future research and practical implications will be presented in Chapter 8.

Table 7-11 Results summarization of the experimental study

Dimension	Factor	Design Phase	Frequency Distribution		Sequence Net	Task Difference	
			Most visited	Least visited		More visited in TDD	More visited in EDD
Knowledge	Knowledge Class	<i>Conceptual Design</i>	TK	PK	consecutively expressing TK, MK and HK	MK, PK	none
		<i>System-level Design</i>	TK	MK	consecutively expressing TK, HK and PK	TK	HK, PK
		<i>Detail Design</i>	TK	MK	consecutively expressing TK	MK, TK	None
		<i>All three Design Phases</i>	Significant increase: TK from C to S Significant decrease: MK from C to S and D		consecutively expressing TK and MK	TK	PK
	Description	<i>Conceptual Design</i>	market, function, cost	software, manufacturing, ergonomics, assembly, maintenance, esthetics, safety	/	geometry, material, position, shape	function
		<i>System-level Design</i>	shape, geometry, function	maintenance, manufacturing, safety, ergonomics, esthetics, software, kinetics, costs	/	position, assembly	material, software
		<i>Detail Design</i>	no significant difference	no significant difference	/	geometry, position, shape, assembly, manufacturing	material, quality
		<i>All three Design Phases</i>	Significant increase: None Significant decrease: Function from S to D, Cost and Market from C to S and D		/	Shape, assembly	function, software, quality
	Level of Detail	<i>Conceptual Design</i>	labeled level	unlabeled level	consecutively expressing knowledge in labeled level and qualitative level	qualitative level	labeled, associative level

		<i>System-level Design</i>	labeled level	unlabeled level	consecutively expressing knowledge in labeled level and quantitative level	quantitative	unlabeled, labeled
		<i>Detail Design</i>	labeled level	unlabeled level	consecutively expressing knowledge in labeled level, qualitative level and quantitative level	qualitative, quantitative	none
		<i>All three Design Phases</i>	no significant difference		consecutively expressing knowledge in labeled level, qualitative level and quantitative level	qualitative and quantitative	labeled level
Activities	Knowledge Activity	<i>Conceptual Design</i>	no significant difference	no significant difference	consecutive knowledge evaluation and knowledge sharing	none	knowledge sharing, evaluation and utilization
		<i>System-level Design</i>	no significant difference	no significant difference	consecutive knowledge sharing	none	knowledge generation, sharing and evaluation
		<i>Detail Design</i>	no significant difference	no significant difference	consecutive knowledge sharing	knowledge generation, sharing, evaluation, utilization	none
		<i>All three Design Phases</i>	no significant difference		consecutive knowledge sharing	none	none
	Team Interaction	<i>Conceptual Design</i>	no significant difference	no significant difference	communicating in 2-way, 1-way and 3-way consecutively; 2-way followed by 3-way, and 3-way followed by 2-way	none	2-way, 3-way
		<i>System-level Design</i>	2-way	4-way	communicating in 2-way and 3-way consecutively; 2-way followed by 3-way, 3-way followed by 2-way, and 2-way followed by 1-way	none	none
		<i>Detail Design</i>	2-way	4-way	communicating in 2-way and 1-way consecutively; 1-way followed by 2-way, 3-way followed by 2-way, and 2-way followed by 3-way	2-way, 3-way	1-way

		<i>All three Design Phases</i>	2-way	4-way	communicating in 2-way and 1-way consecutively; 2-way followed by 3-way, 3-way followed by 2-way, and 2-way followed by 1-way	none	none
	Decision Making	<i>Conceptual Design</i>	alternative	outcome	consecutively quoting criteria and generating alternative	none	alternative and decision
		<i>System-level Design</i>	alternative	outcome	consecutively generating alternative	alternative and criteria	objective and decision
		<i>Detail Design</i>	alternative	outcome	consecutively generating alternative; identifying objective followed by generating alternative	all levels of decision making	none
		<i>All three Design Phases</i>	no significant difference		consecutively generating alternative	alternative	decision
Design Space	Level of Abstraction	<i>Conceptual Design</i>	purpose	abstract function	consecutively visiting purpose and generalized function	generalized function	physical function and purpose
		<i>System-level Design</i>	generalized function	abstract function	consecutively visiting generalized function, physical form and purpose	generalized function	purpose
		<i>Detail Design</i>	generalized function	abstract function	consecutively visiting generalized function and purpose	generalized function and physical form	abstract function and purpose
		<i>All three Design Phases</i>	Significant increase: generalized function from C to S Significant decrease: purpose level from C to S, and from S to D.		consecutively visiting generalized function and purpose	generalized function and physical form	purpose, abstract function and physical function
	Level of Aggregation	<i>Conceptual Design</i>	concept evaluation	remaining design planning	consecutively evaluating concept	concept evaluation	concept refinement, remaining design plan
		<i>System-level Design</i>	function unit	component	consecutively visiting function unit, whole system and assembly	assembly and function unit	component, subsystem and whole system
		<i>Detail Design</i>	detail action	preliminary design	consecutively visiting detail action level, objective structuring and refinement	all levels of aggregation	none

Note: C: conceptual design, S: System level design, D: Detail design; TDD: Transportation Device Design, EDD: Electronic Device Design; /=not studied

Chapter 8 Results Discussion and Implications

8.1 Introduction

Many existing knowledge-based systems integrate poorly with the design process. An improved understanding of the knowledge handling is critical to improve knowledge management. Understanding of how people value knowledge to make decisions is essential to knowledge-based system support. The knowledge modeling method can result in a better understanding of the knowledge. It may also be used to create a natural integration of knowledge systems into the design process. Based on the results and discussion, this Chapter provides both theoretical implications for academic research and practical implications for supporting design cognition in knowledge-based systems.

8.2 Theoretical Implications

8.2.1 Understanding the Knowledge in Design

8.2.1.1 Knowledge Class

1) Analysis of the Frequency Distribution

The frequency change of the knowledge class supports the prediction in H1 that each knowledge class plays different roles in different design phases. The results support the hypothesis that the use of market knowledge (MK) significantly decreases from conceptual design to the other two design phases. MK represents the knowledge interacting with external sources such as customers. It is reasonable that MK is less in demand for system and detailed design phases.

When going from conceptual design to system design, there was a significant increase of the use of technology knowledge (TK). However, the prediction of significant increase of TK from system design to detail design was not supported. The result can be interpreted in several ways. Most products require high-technology, and it seems important to use more technology when the design work progresses into system level design. In detail design phase, the results show that TK is still largely needed.

However, it is possible that there is no significant increase of TK from system level to detail design since a large amount of TK is also needed in system level design. Another explanation may be due to the difficulty in capturing TK in detail design since more individual work is needed and thus less verbal communication can be captured.

It was found that human knowledge (HK) is related with idea generation. It is the source of innovation and knowledge generation. It was also found that HK was largely used in conceptual design. However, the hypothesis of significant decrease of HK from conceptual design to the other two design phases was not supported. This may imply that designers also generate many ideas and new knowledge in system level design and detail design. Since HK mainly presents new knowledge, it may be inferred that innovation not only happens in conceptual design, but also in system level design and detail design.

Procedural knowledge was the least used during the whole design, but it was important for guiding the design process. PK is a necessary part of design knowledge. The non-significant change of PK between design phases was supported. This result may be explained in several ways. First, the rapid market changes require quick responses. As a result, the design team has to plan its schedule well in all design phases, since any delay in one design phase will postpone the whole product design process. Second, team collaboration requires the design team to control each design phase. Third, it may be due to the low frequency of usage in each design phase and thus there was no large difference between phases.

2) Analysis of Sequence Net

The knowledge class sequence nets present an understanding of the continuous knowledge processing in all three design phases. They describe the designer's steps in utilizing different classes of knowledge. It was found that designers prefer using the same kind of knowledge continually, for example, for concept refinement designers prefer using TK again after using TK. Most of the time designers prefer consecutively expressing TK and HK. It may be inferred that knowledge processing is a continuous process in design, but it is possible that designers can be interrupted and thus change to a different knowledge class.

3) Analysis of Profile Plots

Profile plots of frequency distribution by knowledge class by task illustrated that knowledge class frequency distribution was not much influenced by tasks in all three design phases. One explanation is that the classification focuses on identifying the knowledge at a high abstractions level. This classification will provide ICT support with better adaptability to different product design contexts. It is necessary to manage the knowledge in this way since most companies today develop a series of products to meet the market. Another explanation for this may be due to the similarity of the two tasks. This study focused on studying portable entertainment products. Both tasks are portable entertainment device designs, requiring high-tech but easily accomplished by designer teams. Increase of the complexity of the design task might influence the knowledge class frequency distribution. Designing products requiring less technology, for example furniture, may have a different frequency distribution.

4) Comparison with Pioneering Studies

Knowledge in design has preciously not been well investigated. This study is an initial study of knowledge in design. It presented a classification of knowledge in design. It is found that the four kinds of knowledge class can well cover all types of knowledge in design. The frequency distribution, sequence net and task difference are analyzed in three design phases.

From the literature review it was found that the use of inappropriate design knowledge can lead to mistakes during product development (Rodgers & Clarkson, 1998). One of the main problems with design knowledge is that most of it exists as separate “islands of knowledge” (Hubka & Eder, 1996). In this study knowledge classification was used to categorize the design knowledge. Frequency distribution and sequence nets provided relationships between these different types of knowledge. These findings may help design support to provide the right knowledge at appropriate times during the design process.

The provision of design support in a computer-based support tool requires structuring and codification of design knowledge (Rodgers & Clarkson, 1998). Generally the codification of unstructured knowledge results in a loss of knowledge or information (Rodgers & Clarkson, 1998). In this study the knowledge was classified in a high

abstraction level, and it seems likely that some information was lost. However, the classification may be useful for designing ICT support for product design. For example, the knowledge class sequence nets may be used.

The results show what type of knowledge is more often visited than other types and at what time. An understanding of the priorities in knowledge utilization would be helpful in presenting the right knowledge at the right time.

8.2.1.2 Description

1) Analysis of the Frequency Distribution

The results supported the prediction in H2 that each description is focused in different design phases. The results also support the hypothesis that market and costs are more considered in conceptual design. This reflects a market-oriented design of the teams. The design teams aimed to design an innovative product for the market, the requirements are well applied in the design. It may also imply that cost has an influential impact on marketing since design team consider both market and cost a lot in conceptual design. It may be inferred that designers try to minimize the cost from the initial stage of product design. It was also found that function is largely considered in conceptual design. It may imply that design teams aimed for designing a successful product by balancing the cost, market and function.

The results validate that geometry is primarily considered in system level design. This is reasonable since system level design requires consideration of relationships of points, lines, angles, surfaces, and solids. Function was also largely considered in system level design. This may be due to the interactive relationships between function and geometry. A change in geometry may influence the function of a product and thus adjustments are needed in both geometry and functionality. It may be inferred that design teams aimed for balancing function with geometry and other physical properties of the products in system level design. It was also found that shape/size was largely considered in system level design. It may also be inferred that there is an interactive relationship between shape/size with function and geometry. This implies that designers move to lower levels of abstraction when going from conceptual design to system level design.

There was no significant difference between descriptions in detail design, and thus the hypothesis that material and shape/size are more considered in detail design was not supported. Shape/size was mostly considered in system level design. It may be inferred that design teams try to ensure all the design characteristics are considered in detail design so as to develop a complete product. The design teams cover all the descriptions during the three design phases. On the one hand, it supports the categories of descriptions in design. On the other hand, it highlights the importance of employing experienced designers for experiment, especially for system level and detail design phases.

Design descriptions provide information on what purpose knowledge is used for in design. It complements the knowledge classification with more detailed information. ICT support with detailed information of description will improve the system to present the right knowledge needed by designers.

2) Analysis of Profile Plots

Profile plots of frequency distribution by description by task illustrated that description frequency distribution was much influenced by tasks in the three design phases. One explanation may be that the different characteristics were focused for different kinds of product. For example, designers concentrated more on shape/size for transportation device, but more on function or software for electronic device.

3) Comparison with Pioneering Studies

Description in conceptual design has been investigated by several researchers (e.g., Baya & Leifer, 1996; Gunther, Frankenberger, & Auer, 1997). This study extended the research by investigating system level design and detail design phases. The frequency distribution and task differences were analyzed in three design phases.

Gunther, Frankenberger, & Auer (1997) found that costs play an important role in conceptual design. They found that the team spends much time in elaborating cost estimates and inferred that design is more cost-oriented. It was also found here that cost was largely visited in conceptual design. Furthermore, this study found that market and function were largely visited. This may imply that design teams balance the cost, market and function. This study also found that market and cost play less important roles in system level and detail design phases. This study also validated the

categories of description in design (Gunther, Frankenberger, & Auer, 1997; Pahl & Beitz, 1993). The results show that the categories of description are also useful for analyzing the descriptions in system level design and detail design.

Radcliffe (1997) found that there are recurring references to the importance of one description in conceptual design. This study also found similar phenomena in system level design and detail design. Baya (1996) suggested that developers of information handling services should identify the characteristics of the descriptions in the context of ICT support and give adequate attention to integrating these characteristics. This study presented an overview of the interpretation of the protocols in three design phases.

8.2.1.3 Level of Detail

1) Analysis of the Frequency Distribution

The results support the prediction in H3 that each level of detail plays a different role in different design phases. The results support the hypothesis that knowledge is mostly expressed in labeled level in conceptual design. This may be due to the rich design experience of the participants. All designers were experienced and thus could label what they wanted to express.

The results do not support the prediction that knowledge is mostly expressed qualitatively in system level design and quantitatively in detail design. It was found that knowledge is mostly expressed in labeled level in system level design as well as in detail design. This may be partly due to the difficulty in quantifying information during design process. Although the designers are very experienced, there were still difficulties in expressing the knowledge quantitatively. It implies that ICT support should provide designers qualitative and quantitative knowledge. Although qualitative and quantitative levels were not significant in the results, they were important for the detail discussion in detail design.

None of the levels of detail produced significant differences between design phases. This implies that designer's behavior in expressing knowledge is not much influenced by design phases.

2) Analysis of Sequence Net

The sequence nets described designer's sequence in using different level of detail in expressing knowledge. It was found that designers preferred consecutively expressing knowledge in labeled level, qualitative level and qualitative level. It may thus be inferred that knowledge expression is a continuous process in design. However, knowledge expression may move to other levels of detail due to the change of topic and other reasons. The level of detail sequence net presents the understanding of the continuous knowledge expression in all three design phases.

3) Analysis of Profile Plots

Profile plots of frequency distribution by level of detail by task illustrated that the level of detail frequency distribution was not much influenced by tasks in the three design phases. One explanation may be that designers are used to expressing knowledge in certain ways. It can also be inferred that designers' behavior in knowledge expression was not much influenced by design contexts or environments.

4) Comparison with Pioneering Studies

Baya (1996) studied designers' transfer between different levels of detail over time in conceptual design. This study extended the investigation of level of detail into system level design and detail design phases. The results showed that the categories of level of detail are useful for analyzing the protocols in system level design and detail design. It was found that knowledge expression in different level of detail did not significantly change in frequency during the different design phases. The frequency distribution, sequence net and task difference were analyzed in three design phases.

Baya (1996) found that the designer moves fluidly between the different levels of detail in conceptual design. They inferred that designers deal with much non-quantitative and non-qualitative information during the conceptual design phase. This study validated Baya's findings in conceptual design. It was also found that knowledge expressions moved fluidly between the different levels of detail in system level design and detail design. Much non-quantitative and non-qualitative information was also found during system level design and detail design phases. Labeled information was used most frequently and unlabeled information the least in all three design phases.

Baya & Leifer (1996) suggested that knowledge support tools should be able to represent and support knowledge at all levels of detail. They also suggested that it is necessary to pay attention to representing unlabelled and associative knowledge in the development of knowledge management tools for conceptual design. This study supports these suggestions. This study also found that it is difficult to express quantitative knowledge during design. It is important for ICT tools to support the presentation of quantitative knowledge during the design process.

The results present the designer's preference in expressing the knowledge, which can be used to prioritize the functionalities of support services and in selecting representations for manipulating information. The support for easy transition between the different levels of detail is essential to support the whole design process. The challenge lies in identifying the relationships among knowledge class, description and level of detail, and providing simple and well integrated mechanisms for presenting the integrated information.

8.2.2 Understanding the Activities in Design

8.2.2.1 Knowledge Activity

1) Analysis of the Frequency Distribution

The results show that all knowledge activities did not significantly change between design phases. The hypothesis H4 that designers have preference in knowledge activity in the different design phase was not supported. This implies that designer's knowledge activities were not much influenced by design phases. It can thus be inferred that design team adheres to certain styles, for example, in most cases knowledge goes through generation, sharing, evaluation and utilization process, although not in any particular order. It may also be inferred that the knowledge activity style is not much influenced by the difference between design phases. It may be related with the design team itself such as the team structure.

There were also no significant differences in frequency between different knowledge activities within each design phase. This may be explained by the frequent change of topic during design. It is found that design progresses as the team focuses and

transfers from topic to topic. Team members were repeatedly engaged in knowledge generation, sharing, evaluation and utilization. Transitions occurred when team members shifted the discussion to another topic or changed the design process. It is also found that transitions of knowledge activities may be prompted by related topics. Transitions also occurred when the topics or process lose steam. The frequent change of topic facilitated changing the involvement of different kinds of knowledge activity. As a result, all the knowledge activities may be as much involved in design.

2) Analysis of Sequence Net

The sequence nets describe designer's sequences in using different kinds of knowledge activity in expressing knowledge. Designers were seldom consecutively involved in just one knowledge activity. There is only little preference in consecutively sharing knowledge. This may support the conjecture in the knowledge activity frequency distribution that design team adheres to certain styles within knowledge activities. This may also support the conjecture that the frequent change of topic facilitated changing the involvement of different kinds of knowledge activity. Knowledge activity sequence net presents the understanding of the continuous knowledge activity involvement in the three design phases.

3) Analysis of Profile Plots

Profile plots of frequency distribution by knowledge activity by task illustrated that knowledge activity frequency distribution was not much influenced by tasks in the three design phases. One explanation may be that designers are used to handling knowledge in certain ways. This supports the conjecture that a design team adheres to certain styles. This may also support the conjecture that the frequent change of topic facilitated changing the involvement of different kinds of knowledge activity. It may also be inferred that the knowledge activity style is not much influenced by the difference between tasks.

4) Comparison with Pioneering Studies

Baya (1996) studied the time varying behavior of the designer among three information activities, namely analyze, access and generate. It was found that the designer moves fluidly between the three stages, jumping back and forth, not spending much time on any of the activities in conceptual design phase. This study defined knowledge activities in four categories: knowledge generation, knowledge sharing, knowledge evaluation and knowledge utilization (Beijerse, 2000; Qiu, Gu, &

Qiu, 2002; Weggeman, 1997). Furthermore, this study extended the investigation of knowledge activity into system level design and detail design phases. It was found that knowledge activities do not significantly change in frequency between design phases. The frequency distribution, sequence net and task difference are analyzed in three design phases. Robert & Veryzer (1998) found that current knowledge management research lacks the dynamics to meet the different requirements from different design processes. The results here may help to solve these problems.

Baya (1996) found that the conceptual design phase is mainly generative and the designer spends a considerable amount of time accessing information. However, this study found that designers were not only active in knowledge generation, but also in sharing, evaluation and utilization. There are no significant differences in frequency between different knowledge activities in the same design phase. Knowledge activity frequency distribution also does not change significantly between design phases. This study found that design team may adhere to certain styles within knowledge activities.

Cross & Cross (1995) noted that listing and framing are used as means of understanding the problem. It is also found that listing and framing are used as means of knowledge activities, especially for knowledge sharing. For example, when a designer tried to share his understanding of the problem to his teammates, an attempt was made to externalize this understanding of the problem, by listing design requirements and specifications. Attempts were also made to create a more internalized understanding, through “framing” the problem in some more intuitive or conceptualized form.

Baykan (1997) found appropriate knowledge for solving design problem can be existing designs and solutions that were previously generated by the designer, using simulation and scenarios, and reasoning from general principles. In this study, it is found that a scenario is a mental simulation carried out in order to identify relevant knowledge about the problem. It is an important means for accessing knowledge from the designer’s long term memory in all three design phases. It helps in making associations between the design situation and the past knowledge. The knowledge can be used to identify constraints or to test a proposed design. Knowledge activities deal with identifying the relevant knowledge for the purpose of identifying constraints. As

design progresses, constraints may be modified or removed based on new knowledge that is generated.

The results present designer's activities in expressing the knowledge, which can be used to prioritize the functionalities of support services. The results lay down the requirement that KM tools should allow designers to move fluidly between different knowledge activities. The challenge lies in identifying the relationships between knowledge and knowledge activity and providing simple and well integrated mechanisms for presenting the integrated information.

8.2.2.2 Team Interaction

1) Analysis of the Frequency Distribution

The results support the prediction in H5 that each team interaction mode plays a different role in different design phases. The results do not support the prediction that team members communicate mostly in 3-way and 4-way in conceptual design. It is found that there is no significant difference between all the team interaction modes in conceptual design. This may imply that team communication was very active in conceptual design. In conceptual design, large amounts of knowledge are manipulated in a short time. It is the most informal and complex phase in design. Decisions and knowledge generated in this phase have a substantial impact on the downstream design process and the overall cost.

In system level design, the team members mostly communicated in 2-way. It may be inferred that system level design requires more collaboration between two persons. Design tasks were divided into different parts and discussed one by one in system level design. Designers with different knowledge backgrounds contributed their own expertise. This may have facilitated the 2-way communication since most of the time the communication was initiated when one team member needed knowledge from another member.

The results do not support the hypothesis that 1-way communication is used mostly in detail design. 2-way communication was used mostly. Design tasks were assigned to different team members from the beginning in detail design phase. However,

communication was still important in detail design phase because any design change would influence the design of other parts. For example, changing the size of one component may influence the position of another component.

2) Analysis of Sequence Net

Team interaction sequence net presents the dynamic change between interaction modes within three design phases. Designers preferred consecutive 2-way communication. A common occurrence noted is that one team member may leave the discussion but another member would then join immediately. Design teams rapidly transferred from one interaction mode to another interaction mode. It is a dynamic process. This can be explained by the frequent changes of topics during design.

3) Analysis of Profile Plots

Profile plots of frequency distributions by team interaction mode by task illustrated that team interaction mode frequency distribution was influenced by tasks in conceptual design and detail design. The interaction mode frequency distribution was not much influenced by tasks in system level design. In conceptual design, it is found that electronic device teams had higher frequency in 2-way and 3-way communication than the transportation device teams. One simple explanation may be that designers had more interest in discussing the electronic device. In detail design, 2-way and 3-way communication were used more but 1-way communication was less used in the transportation device design. This may be due to the greater need for collaboration. Transportation device has more complex relationships between components and designers had to keep communicating so as to integrate well the whole product in detail design.

4) Comparison with Pioneering Studies

This study is an initial investigation of team interaction mode in design. It defined team interaction mode based on the number of team members involved. Furthermore, this study investigated the team interaction mode change in conceptual design, system level design and detail design phases. The frequency distribution, sequence net and task difference are analyzed in three design phases. The findings may be helpful for setting up a more efficient communication mechanism within design processes.

Chiu (2002) investigated the role of organization in design collaboration and how it affects design communication and collaboration. He suggested that a structured organization can facilitate design communication and consequently contribute to the success of the design project. Chiu (2002) suggested that computer supported collaborative work should support three levels of communication, including individual, group and project. This recent study found that team interaction affects design communication and performance. ICT support for design should support four levels of communication, individual, team, interaction mode and task.

The team was composed of four designers, whose behavior and contributions to the team's work were different. Although all team members participated, some came up with many innovative ideas, while others investigated the consequences of design. Some team members pushed the work in a creative direction, while others stepped in only when they felt that they could contribute.

It is clear that teamwork is a social process, and therefore social interactions, roles and relationships must be considered in the analysis of design activity. But such a study is beyond the scope of the present investigation.

8.2.2.3 Decision Making Activity

1) Analysis of the Frequency Distribution

The results support the prediction in H6 that each decision making activity plays a different role in different design phases. Design team members focused on generating alternatives in conceptual design. However, they did not focus on identifying objectives in conceptual design. One explanation is that the task was clear. Rich design experience of the participants may be another explanation for the results. Experienced designers may quickly understand the objectives and clearly know what they are going to do during design.

The results did not support the hypothesis that designers focus on using criteria for evaluation in system level design and decision making in detail design. The alternative level was the most visited whereas outcome level was the least visited in all three design phases. There are several explanations for why the alternative was the

most visited. First, it may be inferred that mostly one decision is made based on numbers of alternatives. During the three design phases designers suggested hundreds of alternatives. However, only few alternatives were further assessed and few decisions were made. Second, one alternative will often lead to a new alternative. A design alternative to solve one objective could be inconsistent with another objective, and thus designer may introduce another alternative so as to satisfy both objectives. There was also evidence that individuals would introduce a new alternative to argue for or against other alternatives.

2) Analysis of Sequence Net

Decision making sequence nets describe designer's sequence in visiting different levels of decision activity. In conceptual design, it was found that designers preferred consecutively quoting criteria. One possible reason is that, in contrast to individually working designers, team members had to communicate their reasons explicitly to contribute to the decision making process. This implies that it is necessary to describe accurately the precise criteria that are relevant to the decision. It was also found that designers consecutively introduced alternatives in three design phases.

3) Analysis of Profile Plots

Profile plots of frequency distribution by decision making activity by task illustrated that decision making frequency distribution was much influenced by tasks in all three design phases. In the conceptual design, more alternatives were generated and more decisions were made in electronic device design. One explanation may be that designers had great interest in discussing electronic devices. In system level design, the transportation device design introduced more alternatives but there were fewer decisions. It may be inferred that it is more difficult to design transportation device than the electronic device in system level design. This is a reasonable assumption since generally transportation device' physical structure is more complex than that of electronic device. Evidence from experiment also showed that it was easier to decompose electronic devices whole system into subsystems or function units. In detail design, all decision making activities especially alternatives are more involved in transportation device design. This may be due to the greater need for collaboration for designing transportation devices. Transportation device designers have to frequently argue with teammates so as to integrate well the whole product in detail

design. As discussed in frequency distribution analysis, more arguments may introduce more alternatives during design.

4) Comparison with Pioneering Studies

Decision making activities in conceptual design phase have been studied by many researchers (e.g., Girod, 2000; Herling, Ullman, & D'Ambrosio, 1995; Ullman, Dietterich, & Stauffer, 1988). The present study extended the investigation of decision making activity into system level design and detail design phases. It was found that decision activities do not significantly change in frequency between design phases. The frequency distribution, sequence net and task difference were analyzed in three design phases. Decision making research at the team level is a new phenomenon (Griffith, Sawyer, & Neale, 2003; Martins, Gilson, & Maynard, 2004). This study has enriched the understanding of team decision making in design.

Ullman et al. (1996) studied the information evolution and decision making process in conceptual design. They demonstrated the usefulness in analyzing protocols based on objects, relationships, issues, alternatives, evaluation and decisions. Based on Ullman's work, this study categorized decision making activities into objective, alternative, criteria, decision and outcome. The segmentation of the protocol into five levels and the further decompositions of each level into sub-segments are consistent with the models offered by Ullman et al. (1996). The results show that the categories are indeed useful for analyzing decision making activities in all three design phases.

Ullman et al. (1996) found that development of multiple alternatives was seen early in the conceptual design. Development of multiple alternatives was also found in system level design and detail design. Akin & Lin (1995) noted that experts have sufficient knowledge from previous experiences to recognize generic patterns. The result here that objective was not often identified in conceptual design may support the findings. Experienced designers recognize generic patterns in design and thus do not need much effort to identify what they are going to do.

Ullman et al. (1996) found that alternatives are often dependent on the resolution of other objectives or alternatives in conceptual design. This phenomenon was also found in system level design and detail design. Ullman et al. (1996) found that an

alternative will often introduce new sub-objectives. In this study, it was found that an alternative often introduced a new alternative in all three design phases. It is also found that mostly one decision was made based on numbers of alternatives

Ullman et al. (1996) found that objectives are dynamic in that they come into existence as needed and their relationships can change with the evolution of the product. The results for the conceptual design experiment validated these findings. However, much evidence showed that the objectives were static in system level design and detail design. This observation is reasonable since conceptual design is more like an open discussion, whereas system level design and detail design are more focused on detail.

Cross & Cross (1995) found that a design argument can close a disagreement. It is probably inevitable that disagreements will arise between members of a design team. However, provided that a team collectively desires to reach an acceptable conclusion to their design task, it will have to find ways of resolving conflicts. In this study many observations illustrate that disagreements may remain unresolved for the sake of expediency. Sometime the disagreement was defused by everyone joking about it. Designers would also shift topic to avoid or postpone a conflict. By using “common sense”, such as quoting principles, theories or storytelling, conflicts can often be resolved.

This study demonstrated the usefulness in modeling decision making activities based on objective, alternatives, criteria, decision and outcome. This study served to verify the existing decision making models and extend the findings from conceptual design to system level and detail design.

8.2.3 Understanding the Design Space

8.2.3.1 Level of Abstraction

1) Analysis of the Frequency Distribution

The results support the prediction in H7 that different levels of abstraction play a different role during different design phases. The results support the hypothesis that

design team members focus on identifying purpose in conceptual design. It is reasonable for designers to focus on purpose level in conceptual design since new product development is only in its initial stage. The results support that purpose level is the highest level of abstraction.

The results also support the hypothesis that team members focus on generalized function in system level design. System level design is a transition period between conceptual design and detail design. In this phase, designers aim for designing a physical form product based on the concept developed in conceptual design phase. Generalized function is at medium level of abstraction connecting the purpose to physical form. This may explain why generalized function was largely visited in system level design. It may also be inferred that there is a movement toward low level of abstraction from conceptual design to system level design.

The results do not support the hypothesis that designers focus on physical form in detail design. This may imply that the whole design process does not strictly follow top-down process from highest abstraction level (purpose) to lowest abstraction level (physical form). The results show that physical form was visited similarly in the three design phases. It may also be inferred that designers do not strictly follow a top-down process in the same design phase. The purpose was also largely visited in system level design and detail design. The generalized function was the most visited in both system level design and detail design. This study inferred that level of abstraction in design process is progressed with a mixture of top-down and bottom-up processing. It was also found that physical function and abstract function do not significantly change in frequency between design phases.

2) Analysis of Sequence Net

Sequence nets of the levels of abstraction describe designer's sequence in visiting different levels of abstraction in design space. A design team can rapidly transfer from one level to another level of abstraction. The results showed that the transfer between abstraction levels is dynamic in design process. It was found that designers preferred consecutively visiting generalized function level and purpose level. This may also support the conjecture that level of abstraction in design process is progressed with a mixture of top-down and bottom-up processing.

3) Analysis of Profile Plots

Profile plots of frequency distribution by abstraction level by task illustrated that abstraction frequency distribution was somewhat influenced by tasks in conceptual design and detail design phases. Abstraction frequency distribution was not much influenced by tasks in system level design.

For the three design phases, generalized function and physical form were more visited in transportation device design. Purpose, abstract function and physical function were more visited in electronic device design. One explanation is that different product characteristics lead to different behavior. The transportation device task was referred more to shape/size but less to function compared with electronic device task. The physical form was important to transportation device, but physical function was more essential to electronic device design.

It was also found that electronic device design was referred more to higher levels of abstraction, such as purpose and abstract function. Whereas transportation device design was referred more to lower levels of abstraction, such as generalized function and physical form. It may be inferred that electronic device design is high abstraction-oriented whereas transportation device design is low abstraction-oriented.

4) Comparison with Pioneering Studies

Rasmussen (1990) described how a problem solving task can be formulated at several levels of abstraction in the representation of design properties. In this study the levels of abstraction are defined according to the Means-ends dimension (Rasmussen, 1990). This study extended the investigation of level of abstraction from conceptual design to system level design and detail design phases. The frequency distributions, sequence nets and task differences were analyzed in the three design phases. This study presents the understanding of the nature of the design process and will help designers to apply appropriate knowledge into the design space.

Cody et al. (1993) studied the process of complex system design by three levels of abstraction: purpose, function and form. They hypothesized that design can be characterized as sequences of the activities that form paths or trajectories across levels of abstraction in the artifact space. The results in this study support their hypothesis.

This study inferred that there is a movement from higher to lower levels of abstraction as the design moves from conceptual design to system level design. This study also found that that top-down process is not strictly followed between design phases or within the same design phase. It was inferred that level of abstraction in design process is progressed with a mixture of top-down and bottom-up processing.

Cody et al. (1993) found that moves along the levels of abstraction can be seen to represent different types of tasks. Moving from higher to lower levels of abstraction is associated with design specification, while design justification goes from lower to higher. This study found that abstraction level frequency distribution is influenced by different characteristics of different kinds of product. This study also inferred that electronic device design is high abstraction-oriented whereas transportation device design is low abstraction-oriented.

Purcell et al. (1997) studied level of abstraction using three levels: system, subsystem and detail. They found that level of abstraction reflects a less rapid rate of change. They inferred that the designer steadily decomposes the problem, beginning at the system level, then considering the subsystems, and finally addressing the detail level. The study found that there is frequent back and forth change between different levels of abstraction. This study concluded that abstraction progress is dynamic in design process. This may be due to the rich design experience of the participants or the interest topic of the design tasks.

Purcell et al. (1997) also found that designers mostly consider the requirements of the problem at the very beginning of the design session. This study found that purpose level was the most visited in conceptual design, but also largely visited in system level design and detail design. The results may reflect that designers constantly adjusted their design according to the purpose level throughout the three design phases.

8.2.3.2 Level of Aggregation

1) Analysis of the Frequency Distribution

The results do not support the hypothesis in H8 that designers focus on concept generation in conceptual design. It was found that concept evaluation was undertaken

the most times among all levels of aggregation in conceptual design. This may be explained in several ways. Clearly it is necessary for a team to generate design concepts, and use the concepts to a specific design proposal. On the one hand, the design team has to evaluate the concepts that are generated. On the other hand, the team has to develop initial concepts into more detailed versions. Therefore a design team has to put much effort in evaluating and improving design. The remaining design planning level is visited with the fewest times, but it was found important for guiding the design process during verbal analysis. It was found that usually there is at least one team member who is conscious of planning the design activities within a team. Despite the conscious planning that the team undertakes, many observations showed that not all activities proceed according to the plan. This may imply that the aggregation progress is dynamic.

The results do not support the hypothesis in H8 that designers focus on the whole system level in system level design. Function unit was visited the most, whereas component was visited with the fewest times. It may be inferred that design teams decompose the product mainly based on function. It is reasonable that a component is the least visited since system level design is targeted at defining the product architecture. This study found that whole system and assembly are also frequently visited. This implies that system level design is targeted at decomposing the whole system and defining the product architecture.

The results support the hypothesis in H8 that designers focus on detail action in detail design. This implies that it is important to observe the designers with experience in detail design phase. It is also important to assign a task to which experienced designers may be able to contribute their expertise. Otherwise, it will be difficult for the participants to progress in detail design. This study also found that all other levels of aggregation in detail design phase are largely visited. It can be inferred that level of aggregation in design process is progressed with a mixture of top-down and bottom-up processing. The results may also imply that a mixture of top-down and bottom-up processing is useful for designers' problem solving. Moving back and forth between aggregation levels may help the design team decompose the problem into understandable parts, and therefore the problem can be easily solved.

2) Analysis of Sequence Net

Sequence nets of level of aggregation describe the designer's sequence in visiting different levels of aggregation in design space. Design teams rapidly transferred from one level of aggregation to another level. The results show that the aggregation progress is dynamic. It was found that designers preferred consecutively evaluating concepts during conceptual design. They moved back and forth more frequently between different levels of aggregation in system level and detail design. This may support the conjecture that the level of aggregation in design is progressed with a mixture of top-down and bottom-up processing.

3) Analysis of Profile Plots

Profile plots of frequency distribution by aggregation level by task illustrated that the aggregation frequency distribution was much influenced by tasks in all three design phases. In conceptual design, concepts were more evaluated but less selected and refined in transportation device design than in electronic device design. This may be that for transportation device design it is more difficult to adopt the concepts for further consideration than in design of electronic device. It may thus be inferred that the transportation device design team argued more for the proposed concepts than the electronic device design team. This may be due to high collaboration requirements for transportation device design. More decisions were made in electronic device design may support this conjecture. This result implies that it is easier to make decisions in electronic device design. Therefore more concepts can be selected and refined as the profile plots showed.

In system level design, assembly was visited more in transportation device design than in electronic device design. One explanation may be that the transportation device has more requirements on product architecture, and thus the assembly level was more visited. Component, subsystem and whole system were discussed more in electronic device design. This seems reasonable because electronic device is mainly composed of electronic components, and thus the component level was more visited.

In detail design, all levels of aggregation were visited more in transportation device design than in electronic device design. Again it may be inferred that transportation device design space is more complex than electronic device design space in detail

design phase. This result supports the conjecture that complexity of design space varies between design tasks in detail design phase.

4) Comparison with Pioneering Studies

In this study level of aggregation is associated with the design phase. This study investigated the level of aggregation in three design phases, including conceptual design, system level design and detail design. The frequency distribution, sequence nets and task differences were analyzed. This study presents the understanding of design aggregation process and may help designers to apply appropriate knowledge into the design space.

Cross & Cross (1995) found that there was explicit planning of activities and time scheduling in conceptual design. This was also found in this study at the system level design and detail design. Although remain design planning level was not frequently visited, it is important for design progress control, especially for teamwork. Despite the conscious planning that the team undertook, some observations show that not all activities proceeded strictly according to the plan. This is consistent with the finding of “opportunistic” behavior of designers, which occurs when designers deviate from planned activities in order to pursue ideas as they occur (Guindon, 1990; Schon & Wiggins, 1992).

Cross & Cross (1995) stated that concepts need to be built up to turn the initial idea into something more robust. They found that persuasive tactics are used to get favored concepts adopted. The statement is supported by this study. This study also found that aggregation progress is dynamic in design process. Design teams rapidly transferred from one level of aggregation to another. Designers preferred consecutively evaluating concepts in conceptual design. This study found that the transportation device design team argued more for the concepts proposed than the electronic device design. The author conjectured that transportation device design may be more difficult in adopting the concepts for further consideration than electronic device design.

Cody et al. (1993) studied the process of complex system design and hypothesized that design can be characterized as sequences of activities that form paths or trajectories across levels of aggregation in the artifact space. This study inferred that

level of aggregation in design process is progressed with a mixture of top-down and bottom-up processing. Cody et al. (1993) further found that decomposition and integration are associated with moves along the aggregation dimension. This study found that design teams decompose the product mainly based on function units. It was also found that system level design is targeted at decomposing the whole system and defining the product architecture. The results imply that a mixture of top-down and bottom-up processing is useful for designers' problem solving, since it may help the design team to decompose the problem into more understandable parts. The results also inferred that the electronic device is more easily decomposed.

Goel & Pirolli (1992) categorized design problem-solving into three categories: preliminary design, refinement, and detail design. In this study levels of aggregation in detail design were classified into objective structuring, preliminary design, refinement, and detail action. Goel & Pirolli (1992) made a conjecture that the distinct phases result from not only the size and the complexity of the problems, but perhaps more importantly, from a combination of the different types of information that must be considered during the session. This study found that the complexity of design space may vary between design tasks in detail design phase. Goel & Pirolli (1992) found that there was still some input from the client at the preliminary design stage, but it disappeared at the detailing stage. This study found that objective structuring was still highly visited. This may imply that customer needs are still used for refining detail design. Goel & Pirolli (1992) also noted that there was a steady increase in the number of verbalizations that were committed to paper as subjects progressed from preliminary design, through refinement, to detail action. The results in detail design phase support the statement. Much evidence also indicated that there was an increase in the degree of explicitness and detailing in the written or drawn material from the conceptual design phase, through system level design, to detail design.

Design is generally described as a hierarchical, somewhat chaotic process involving transitions back and forth between synthesis and analysis at several levels of abstraction and aggregation (Cody, Rouse, & Boff, 1993). Various attempts have been made to organize design activities into prescribed steps, typically involving a top-down or bottom up hierarchical process. These approaches have the advantage of fostering systematic evolution of solutions, but the disadvantage of potentially

inhibiting insights and innovation (Cody, Rouse, & Boff, 1993). This study proposed a framework and method for investigating the design space in three design phases. Some interesting results were yielded. As design ideas or solutions were generated, they were evaluated, refined and incrementally aggregated until they reached their final form. Associated knowledge was integrated into the design space throughout the design process. The design space may be a function of the knowledge available. The key findings are summarized and interpreted in Table 8-1.

8.2.4 Understanding the Relationships of Knowledge, Activities and Design Space

The former part of this study presented the understanding on factors of knowledge, activity and design space. This study also investigated the relationships among these factors. The results of the relationships among different factors of knowledge, i.e., the relationships among knowledge class, description and level of detail, presented a deeper representation of the content of knowledge. The results of the relationships among different factors of activity, i.e., the relationships among knowledge activity, team interaction mode and decision activity, made it possible to understand the actions on knowledge. The results of the relationships among different factors of design space, i.e., the relationships among level of abstraction and aggregation, presented the understanding on the context of knowledge.

This study also investigated the interactive relationships among knowledge, activity and design space. The interactive relationships between knowledge and activity presented the understanding on how knowledge is shared and utilized. The interactive relationships between knowledge and design space presented the understanding on how knowledge is integrated with the design space. The interactive relationships between activity and design space presented the understanding on how the design is progressed.

Design methodology should describe the design process as an integration of knowledge, activities and design space. It is important to investigate the relationships of knowledge, activity and design space. For example, it is interesting to understand how knowledge classes influence the design decisions, particularly those that

represent important features of the design. The coincidence between decision activities and knowledge class may be not the result of pure chance. Decision making and knowledge class may have causal relationships that can be captured. It may be inferred that there is some predictability among knowledge, activity and design space. In this study some results were presented in Chapter 7. However, to extract clear understanding from those results would need much more elaboration and follow-up studies. The author hopes that future research may continue to investigate these issues. A better understanding would greatly improve ICT support for design.

Table 8-1 Summarization of key findings and interpretation in experimental study

Dimension	Factor	Design Phase	Results Analysis	
			Key Findings	Interpretation
Knowledge	Knowledge Class	<i>Frequency Distribution</i>	<ol style="list-style-type: none"> 1. The prediction in H1 that each knowledge class plays different roles in different design phases is supported. It also supports the hypothesis that the use of MK significantly decreases from conceptual design to the other two design phases. 2. The prediction of significant increase of TK from system design to detail design is not supported. 3. HK is related with idea generation. However, the hypothesis of significant decrease of HK from conceptual design to the other two design phases is not supported. 4. The non-significant change of PK between design phases was supported. 	<ol style="list-style-type: none"> 1. MK represents the knowledge interacting with external sources such as customers. It is reasonable that MK is less in demand for system and detailed design phases. 2. Most products require high-technology. Another explanation may be due to the difficulty in capturing TK in detail design since more individual work is needed and thus less verbal communication can be captured. 3. This may imply that designers also generate many ideas and new knowledge in system level design and detail design. Since HK mainly presents new knowledge, it may be inferred that innovation not only happens in conceptual design, but also in system level design and detail design. 4. First, the rapid market changes require quick responses. As a result, the design team has to plan its schedule well in all design phases, since any delay in one design phase will postpone the whole product design process. Second, team collaboration requires the design team to control each design phase.
		<i>Sequence Net</i>	<ol style="list-style-type: none"> 1. Designers prefer using the same kind of knowledge continually. Most of the time designers prefer consecutively expressing TK and HK. 	<ol style="list-style-type: none"> 1. Knowledge processing is a continuous process in design, but it is possible that designers can be interrupted and thus change to a different knowledge class.
		<i>Task Difference</i>	<ol style="list-style-type: none"> 1. Frequency distribution was not much influenced by tasks in all three design phases. 	<ol style="list-style-type: none"> 1. The classification focuses on identifying the knowledge at a high abstractions level. There are some similarities of the two tasks.
		<i>Comparison with Pioneering Study</i>	<ol style="list-style-type: none"> 1. This study is an initial study of knowledge in design. It presented a classification of knowledge in design. 	

	Description	Frequency Distribution	<div><div>1. The results supported the prediction in H2 that each description is focused in different design phases. The results also support the hypothesis that market and costs are more considered in conceptual design.</div><div>2. Function is largely considered in conceptual design.</div><div>3. The results validate that geometry is primarily considered in system level design.</div><div>4. The hypothesis that material and shape/size are more considered in detail design is not supported.</div></div>	<div><div>1. This reflects a market-oriented design of the teams. It may also imply that cost has an influential impact on marketing since design team consider both market and cost a lot in conceptual design. It may be inferred that designers try to minimize the cost from the initial stage of product design.</div><div>2. Design teams aimed for designing a successful product by balancing the cost, market and function.</div><div>3. This is reasonable since system level design requires consideration of relationships of points, lines, angles, surfaces, and solids.</div><div>4. It may be inferred that design teams try to ensure all the design characteristics are considered in detail design so as to develop a complete product.</div></div>	
		Task Difference	<div><div>1. Frequency distribution was much influenced by tasks in the three design phases</div></div>	<div><div>1. Different characteristics were focused for different kinds of product.</div></div>	
		Comparison with Pioneering Study	<div><div>1. This study extended the research by investigating system level design and detail design phases. The frequency distribution and task differences were analyzed in three design phases.</div><div>2. This study also validated the categories of description in design (Gunther, Frankenberger, & Auer, 1997; Pahl & Beitz, 1993).</div></div>		
	Level of Detail	Frequency Distribution	<div><div>1. The results support the prediction in H3 that each level of detail plays a different role in different design phases. The results support the hypothesis that knowledge is mostly expressed in labeled level in conceptual design.</div><div>2. The results do not support the prediction that knowledge is mostly expressed qualitatively in system level design and quantitatively in detail design.</div><div>3. None of the levels of detail produced significant differences between design phases.</div></div>	<div><div>1. Rich design experience of the participants. All designers were experienced and thus could label what they wanted to express.</div><div>2. It implies that ICT support should provide designers qualitative and quantitative knowledge. This may also be partly due to the difficulty in quantifying information during design process.</div><div>3. Designer’s behavior in expressing knowledge is not much influenced by design phases.</div></div>	
		Sequence Net	<div><div>1. It was found that designers preferred consecutively expressing knowledge in labeled level, qualitative level and qualitative level.</div></div>	<div><div>1. Knowledge expression is a continuous process in design.</div></div>	
		Task Difference	<div><div>1. Frequency distribution was not much influenced by tasks in the three design phases.</div></div>	<div><div>1. Designers are used to expressing knowledge in certain ways. It can also be inferred that designers’ behavior in knowledge expression was not much influenced by design contexts or environments.</div></div>	
		Comparison with Pioneering Study	<div><div>1. This study extended the investigation of level of detail into system level design and detail design phases. The frequency distribution, sequence net and task difference were analyzed in three design phases.</div></div>		
	Activities	Knowledge Activity	Frequency Distribution	<div><div>1. The hypothesis H4 that designers have preference in knowledge activity in the different design phase was not supported.</div><div>2. There were also no significant differences in frequency between different knowledge activities within each design phase.</div></div>	<div><div>1. Design team adheres to certain styles.</div><div>2. This may be explained by the frequent change of topic during design.</div></div>

		<i>Sequence Net</i>	1. Designers were seldom consecutively involved in just one knowledge activity. There is only little preference in consecutively sharing knowledge.	1. Design team adheres to certain styles within knowledge activities. The frequent change of topic facilitated changing the involvement of different kinds of knowledge activity.
		<i>Task Difference</i>	1. Frequency distribution was not much influenced by tasks in the three design phases.	1. Designers are used to handling knowledge in certain ways. Design team adheres to certain styles. The frequent change of topic facilitated changing the involvement of different kinds of knowledge activity.
		<i>Comparison with Pioneering Study</i>	1. This study defined knowledge activities in four categories: knowledge generation, knowledge sharing, knowledge evaluation and knowledge utilization. 2. This study extended the investigation of knowledge activity into system level design and detail design phases.	
	Team Interaction	<i>Frequency Distribution</i>	1. The results support the prediction in H5 that each team interaction mode plays a different role in different design phases. The results do not support the prediction that team members communicate mostly in 3-way and 4-way in conceptual design. 2. In system level design, the team members mostly communicated in 2-way. 3. The results do not support the hypothesis that 1-way communication is used mostly in detail design. 2-way communication was used mostly.	1. Team communication was very active in conceptual design. 2. System level design requires more collaboration between two persons. 3. Communication was still important in detail design phase because any design change would influence the design of other parts.
		<i>Sequence Net</i>	1. Designers preferred consecutive 2-way communication. Design teams rapidly transferred from one interaction mode to another interaction mode.	1. It is a dynamic process. This can be explained by the frequent changes of topics during design.
		<i>Task Difference</i>	1. Frequency distribution was influenced by tasks in conceptual design and detail design. The interaction mode frequency distribution was not much influenced by tasks in system level design.	1. Designers had more interest in discussing the electronic device. Transportation device has more complex relationships between components and designers had to keep communicating so as to integrate well the whole product in detail design.
		<i>Comparison with Pioneering Study</i>	1. This study is an initial investigation of team interaction mode in design. It defined team interaction mode based on the number of team members involved. Furthermore, this study investigated the team interaction mode change in conceptual design, system level design and detail design phases. The frequency distribution, sequence net and task difference are analyzed in three design phases.	
	Decision Making	<i>Frequency Distribution</i>	1. The results support the prediction in H6 that each decision making activity plays a different role in different design phases. However, they did not focus on identifying objectives in conceptual design. 2. The results don't support the hypothesis that designers focus on using criteria for evaluation in system level design and decision making in detail design. The alternative level was the most visited whereas outcome level was the least visited in all three design phases.	1. The task was clear. Rich design experience of the participants may be another explanation for the results. 2. First, it may be inferred that mostly one decision is made based on numbers of alternatives. Second, one alternative will often lead to a new alternative. There was also evidence that individuals would introduce a new alternative to argue for or against other alternatives.

		<i>Sequence Net</i>	1. In conceptual design, designers preferred consecutively quoting criteria.	1. One possible reason is that, in contrast to individually working designers, team members had to communicate their reasons explicitly to contribute to the decision making process. This implies that it is necessary to describe accurately the precise criteria that are relevant to the decision.
		<i>Task Difference</i>	1. Frequency distribution was much influenced by tasks in all three design phases. In the conceptual design, more alternatives were generated and more decisions were made in electronic device design. 2. In system level design, the transportation device design introduced more alternatives but there were fewer decisions. 3. In detail design, all decision making activities especially alternatives are more involved in transportation device design.	1. Designers had great interest in discussing electronic devices. 2. It is more difficult to design transportation device than the electronic device in system level design. This is reasonable since generally transportation device' physical structure is more complex than that of electronic device. 3. This may be due to the greater need for collaboration for designing transportation devices. Transportation device designers have to frequently argue with teammates so as to integrate well the whole product in detail design.
		<i>Comparison with Pioneering Study</i>	1. This study demonstrated the usefulness in modeling decision making activities based on objective, alternatives, criteria, decision and outcome. This study served to verify the existing decision making models and extend the findings from conceptual design to system level and detail design.	
Design Space	Level of Abstraction	<i>Frequency Distribution</i>	1. The results support the prediction in H7 that different levels of abstraction play a different role during different design phases. The results support the hypothesis that design team members focus on identifying purpose in conceptual design. The results support that purpose level is the highest level of abstraction. 2. The results also support the hypothesis that team members focus on generalized function in system level design. 3. The results do not support the hypothesis that designers focus on physical form in detail design.	1. It is reasonable for designers to focus on purpose level in conceptual design since new product development is only in its initial stage. 2. Generalized function is at medium level of abstraction connecting the purpose to physical form. It may also be inferred that there is a movement toward low level of abstraction from conceptual design to system level design. 3. This may imply that the whole design process does not strictly follow top-down process from highest abstraction level (purpose) to lowest abstraction level (physical form). This study inferred that level of abstraction in design process is progressed with a mixture of top-down and bottom-up processing.
		<i>Sequence Net</i>	1. A design team can rapidly transfer from one level to another level of abstraction. 2. It was found that designers preferred consecutively visiting generalized function level and purpose level.	1. The transfer between abstraction levels is dynamic in design process. 2. The level of abstraction in design process is progressed with a mixture of top-down and bottom-up processing.
		<i>Task Difference</i>	1. Frequency distribution was somewhat influenced by tasks in conceptual design and detail design phases. It was not much influenced by tasks in system level design. 2. Electronic device design was referred more to higher levels of abstraction, such as purpose and abstract function. Whereas transportation device design was referred more to lower levels of abstraction, such as generalized function and physical form.	1. Different product characteristics lead to different behavior. 2. It may be inferred that electronic device design is high abstraction-oriented whereas transportation device design is low abstraction-oriented.

		Comparison with Pioneering Study	1. This study extended the investigation of level of abstraction from conceptual design to system level design and detail design phases. The frequency distributions, sequence nets and task differences were analyzed in the three design phases.	
	Level of Aggregation	Frequency Distribution	1. The results do not support the hypothesis in H8 that designers focus on concept generation in conceptual design. Concept evaluation was undertaken the most times among all levels of aggregation in conceptual design. 2. The results do not support the hypothesis in H8 that designers focus on the whole system level in system level design. Function unit was visited the most, whereas component was visited with the fewest times. 3. The results support the hypothesis in H8 that designers focus on detail action in detail design. 4. All levels of aggregation in detail design phase are largely visited.	1. The design team has to evaluate the concepts that are generated. Furthermore, the team has to develop initial concepts into more detailed versions. Therefore a design team has to put much effort in evaluating and improving design. 2. It may be inferred that design teams decompose the product mainly based on function. 3. This implies that it is important to observe the designers with experience in detail design phase. 4. Level of aggregation in design process is progressed with a mixture of top-down and bottom-up processing. The results may also imply that a mixture of top-down and bottom-up processing is useful for designers' problem solving.
		Sequence Net	1. The aggregation progress is dynamic. Designers preferred consecutively evaluating concepts during conceptual design.	1. Level of aggregation in design is progressed with a mixture of top-down and bottom-up processing.
		Task Difference	1. Frequency distribution was much influenced by tasks in all three design phases. 2. In conceptual design, concepts were more evaluated but less selected and refined in transportation device design than in electronic device design. 3. In system level design, assembly was visited more in transportation device design than in electronic device design. 4. In detail design, all levels of aggregation were visited more in transportation device design than in electronic device design.	1. The complexity of design space varies between design tasks in different design phases. 2. It may thus be inferred that the transportation device design team argued more for the proposed concepts than the electronic device design team. This may be due to high collaboration requirements for transportation device design. 3. The transportation device has more requirements on product architecture, and thus the assembly level was more visited. 4. Transportation device design space is more complex than electronic device design space in detail design phase.
		Comparison with Pioneering Study	1. In this study level of aggregation is associated with the design phase. This study investigated the level of aggregation in three design phases. The frequency distribution, sequence nets and task differences were analyzed.	

8.3 Practical Implications for Ideal Cognitive Support for Knowledge-based Collaborative Decision Making

There are many kinds of knowledge. In some instances the knowledge is simply not available to designers, but in many cases, available knowledge is overlooked, misunderstood, or misapplied (Cody et al., 1993). Deficiencies vary with the product domain, but the source of the problems is similar: useful knowledge about market, technology, procedure and human etc. is available, but is often not being factored into design decisions. Many of these transfer failures are associated with knowledge that is external to the design team.

8.3.1 Knowledge Support for Collaborative Decision Making

For a product design team, the aim of system support, team environment improvement and other assistance is to support team members to access the required knowledge and to utilize the knowledge for product design. Figure 8-1 depicts the overall support objectives in terms of a combination of two types of task and two types of intervention. As far as knowledge support for product design is concerned, it is essential to support designers with knowledge as well as protect designers from being overwhelmed by unnecessary knowledge (Qiu et al., 2004a). Thereby, one can facilitate sharing and utilizing useful knowledge whereas redundant knowledge is discarded.

Figure 8–1 Four classes of knowledge support for designer collaborative decision making

Knowledge access and utilization, illustrated by the left and right circles in Figure 8-1, represent the target for support. Knowledge access refers to activities that produce an object from the knowledge world for subsequent use; utilization refers to operations performed on or with an object to support problem solving and decision making (Cody et al., 1993; Qiu et al., 2004a). Team collaboration and system support, illustrated by the top and bottom circles in Figure 8-1, represent the two types of intervention for support. System support refers to augmenting designer's performance directly, often through automated means; it involves adapting the environment to the designer in order to complement the designer's style and abilities to overcome his or her limitations (Cody et al., 1993). Team collaboration refers to improving designer's performance through communication, knowledge sharing and other collaborative activities within a team; the designer will be required to interact with the external environment, to acquire knowledge from team members or learn from others.

As suggested by the intersection regions in Figure 8-1, mapping the two types of support on the two types of tasks yields four support classes. The designer can access required knowledge with the support of system or through team collaboration, and he/she can utilize knowledge to solve problems and make better decision with the support of system and team collaboration.

8.3.2 Supporting the Content, Action and Context of Knowledge

Knowledge modeling can obtain a large amount of information about knowledge. The content, action and context of knowledge can be captured. The ideal cognitive support for knowledge-based system is illustrated in Figure 8-2.

Figure 8-2 The ideal cognitive support for knowledge-based system

As illustrated in Figure 8-2, for knowledge database, each knowledge class should be supported by one sub-database. The content, action and context of each knowledge fragment should be provided and managed. ICT support provides the platform for the actions on knowledge. Knowledge is managed, shared and utilized. Knowledge is shared through team collaboration and is utilized for decision making in product design. Knowledge is applied in the context of product design process.

Cognitive support for knowledge-based system should focus on supporting the content, action and context of knowledge. It can be summarized as follows:

Cognitive support for the content of knowledge:

- Providing different knowledge classes support in design
- Supporting designer's description concentration movement in design
- Supporting designer's different level of detail in knowledge expression
- Supporting different knowledge forms in design

Cognitive support for the action on knowledge:

- Supporting different kinds of knowledge activities in design
- Supporting different kinds of team interaction modes in design
- Supporting different kinds of decision making activities in design

Cognitive support for the context of knowledge:

- Providing the context of level of abstraction during design
- Providing the context of level of aggregation during design

Other cognitive support should also be provided according to different focus, such as the relationships of content, action and context.

8.3.3 Leverage on System Support for Knowledge Access and Utilization

According to Cody et al. (1993), decision makers evaluate the sources of knowledge in terms of their potential to reduce uncertainty, apply to an important concern, be accessible, and be in an appropriate form. In order to support decision making, knowledge should be transferred to the right person at the right time of decision making process. Several implications can be summarized for leveraging on system support (Rouse, 2002; Cody et al., 1993):

- A system that supports knowledge access and utilization in general should enable the user to access highly valued knowledge. Decision makers access a wide variety of knowledge, and some types of knowledge are more important than others, such as customer requirements. It is essential to give priority to access those highly valued knowledge so as to leverage on system support for decision making.
- It is essential to understand the knowledge flow in decision making processes. To deliver relevant knowledge to the right person at the right time, the system needs to know what kinds of knowledge is needed in different decision making processes. A support system must be told what the decision maker is attempting to do in the next step, and thereby structure the delivered information so that it is relevant to the decision making processes. This is indeed a difficult task.
- It is valuable to understand the importance of the various types of knowledge at different stages of decision making. To encourage the decision maker's consideration of a particular type of knowledge, knowledge must increase the perceived importance associated with its use and thus reduce costs in obtaining and applying it.

It is thus essential to determine why decision makers often fail to consider potentially valuable knowledge in making decisions. Defining the knowledge flow clearly as well

as a better appreciation of the decision making process will enhance the system support for collaborative decision making in product design.

8.4 Conclusions

In this chapter, theoretical implications for academic research and practical implications for ideal cognitive supports for knowledge-based collaborative decision making were presented. Theoretical implications will contribute to the future research in knowledge management, team collaboration, decision making, product design and ICT support. This study explored new areas for future research. However, this study mainly presents initial concepts for implications. Much work is needed for addressing further applications in the future study.

Chapter 9 Discussions and Future Work

9.1 Introduction

This chapter presents the main conclusions drawn from the research, including the literature review, the research approach, methodology developed and the findings. It states the contributions of this thesis as well as the opportunities for future research.

9.2 Contributions

This research is a multidisciplinary study. It crosses management, engineering and human factors science. It covers knowledge management, team collaboration, decision making and ICT support. For each area, research was mainly focused on knowledge issues in product design.

The research adds knowledge to the fields of knowledge management, team collaboration, decision making, ICT support and engineering design research. It explores the knowledge management research in a human factors perspective. It corroborates verbal protocol analysis as a valuable method for studying knowledge, activities and design space.

A methodology for incrementally understanding and support of the product design process was presented and method for knowledge modeling was developed. Experiments were conducted for exploring the understanding of knowledge sharing and utilization in three product design phases. It shows that the verbal protocol method is useful for studying team designers. A procedure was described for analyzing protocol data to extract an understanding of the knowledge, activity and design space. It presents a knowledge-based collaborative decision making coding framework for studying the knowledge handling behavior of designers. The experiment results provide rich insight for developing successful knowledge-based systems.

The main contributions can be briefly described as follow:

- Identified the main factors for the support of knowledge-based collaborative decision making. This includes:
 - Knowledge-related issues that designers are concerned with in collaborative decision making in product design
 - Factors that should be supported in knowledge-based collaborative decision making in product design
- Developed a methodology for supporting knowledge-based collaborative decision making in product design. This includes:
 - A KCDM model for product design
 - A knowledge modeling method
 - A protocol coding framework for studying knowledge, activity and design space
- Explored the understandings of knowledge-based collaborative decision making in product design. This includes:
 - Findings from an experimental study of experienced designers
 - Understanding on how designers approach product design activities
- Leveraging ICT support for knowledge-based collaborative decision making in product design. This includes:
 - Improving ICT support for knowledge sharing and utilization
 - Optimizing virtual team collaboration process
 - Improving decision making process
 - Providing implications for knowledge-based system support

9.3 Limitations

There are also several limitations of this research and the results have to be viewed in the light of these limitations that are inherent to both the experiment and to the analysis methods. The experimental study limitations are related to the methodology of thinking aloud, the number of cases, the type of task, the type of environment, the subjects and the protocol analysis method.

To be able to record the design process, the designers were asked to think aloud. Though considered to be easy to learn and not very distracting, thinking aloud might have changed the designer's way of working.

The sample size is limited. However, a large amount of design protocols were analyzed for the five design teams. Protocol analysis can produce detailed information of team behavior. However, it is often not practical to study a statistically large sample for each of the scenarios and perspectives that are observed in a design process.

In choosing a task for this type of experiment, a tradeoff has to be made between time and suitability for team designers. The task was relatively simple so that it would be feasible for designers to go through the whole design process within a short period. More complex tasks might show differences in team work. There might be more need to collaborate, and specialist knowledge might force team members into different roles.

Although a laboratory environment is an advantage for comparative research, it restricts the design process and thus the variables in a study. The designers had to work in a room where every action and utterance were observed and recorded. They were not surrounded by their own 'tools' and had to work with the information provided. However, this is expected to be the same for all teams in this study. This study simulated well the real design environment and all the designers were comfortable in their work.

The subjects were all experienced designers, but their level and type of experiences varied. This could thus have affected the findings described in this study. Another subject-related limitation of this type of study is what Denzin (1978) calls the demand-characteristic effect. This might have resulted in designers working more systematically than usual.

The analysis of protocols has its specific limitations. Video recordings and their protocols can be analyzed in a variety of ways. One of the basic activities involved in protocol analysis is the division of the protocol into units that are coded according to a classification scheme. Various schemes can be applied, depending on the aim of the study, and sources used to develop the scheme can differ. Although this dissertation shows that protocol studies have the potential for providing a detail and rich

understanding, it also illustrates that the process of conducting the experimental studies and analyzing the protocol data is a long, tedious and a subjective process. The complexity of the design process presents many challenges in understanding and supporting it. However, because of the success of protocol studies the interest in using this approach is growing. Therefore, like in any new research field, the design research community faces the challenge of establishing mechanisms for validation and comparing results across researchers. This will enable new research to build on top of results already available.

9.4 Future Work

This dissertation raises numerous opportunities for further research. A natural extension, in the interest of the iterative methodology presented, would be to use the results and practical implication stated in the Chapter 7 and 8 to develop knowledge-based systems. The theoretical implications in Chapter 8 suggested many areas for future research.

The KCDM model describes the designer's thinking process during design, whereas cognitive knowledge modeling method provides the understanding of cognitive support on the designer's thinking for knowledge-based system. However, it is found that gaps exist between the cognitive research and real implementation in companies. Implications for future research directions are explored as follows:

1) Implications for future research on knowledge management in product design

Based on the understanding of designer's knowledge processing in product design, there are several implications:

- It is necessary to explore the understanding of designers' thinking process
- It is necessary to specify a knowledge system that can help design participants to obtain relevant knowledge
- Knowledge should be supported differently in different stages of product design
- Knowledge must increase the perceived importance associated with its use to encourage the decision maker's consideration

- It is necessary to leverage on knowledge across functional departments and workers to enable an efficient and timely product design

From a cognitive perspective, the future research on knowledge management in product design could focus on:

- Understanding why designers use some types of knowledge and discard others (Cody, Rouse, & Boff, 1993)
- Identifying the knowledge in product design
- Understanding characteristics of knowledge that designers value by distinguishing what designers use from what they ignore
- Defining the knowledge flow in product design

2) Implications for future research on team collaboration in product design

Team culture, task allocation, policies and so forth greatly influence the designer's performance. Much work has been done for improving team environment. Macmillan (2001), for example, described six characteristics of a high performance team: common purpose, crystal clear roles, accepted leadership, effective processes, solid relationships and excellent communication. However, little work has been done on how to optimize team processes for decision making.

Based on the understanding of designers' collaboration in product design, several implications can be stated:

- It is important to state goals clearly at the outset of design and to keep team members updated on possible changes of goals
- Non-verbal communication should be supported by technology
- The roles distributed among team members must be clear at the outset to avoid duplication of efforts and also to ensure proper accountability
- It is necessary to consider the influence of different cultural background on evaluation norms

Future research could focus on the team cognition in design:

- Understanding the changes of goals in team collaboration
- Understanding designer's communication behavior in a team environment
- Understanding the distribution of roles during design

- Understanding norms such as acceptable behavior during design
- Understanding the importance of leadership
- Developing methodology for measuring team performance

3) Implications for future research on decision making in product design

Knowledge requirements vary during the decision making process. It is important to understand how people make decisions, how time pressures and limitations affect the process, and how systems design can support and enhance decision making.

Several implications can be summarized for decision making:

- It is essential to understand the knowledge flow in decision making process
- It is necessary to define decision making process clearly
- It is necessary to know what knowledge is relevant to decisions
- Adequate information about team members' knowledge and expertise is useful
- It is necessary to understand conflicts among team members
- It is valuable to understand the importance of various types of knowledge for design decision making

From a cognitive perspective, future research on decision making in product design could focus on:

- Understanding designers' process in utilizing knowledge for decision making
- Understanding design situation and designers' team awareness during design
- Identifying natural flow of decision making process
- Developing methodology for knowledge measuring
- Enhancing the motivation for knowledge sharing

4) Implications for future research on ICT support in product design

New generation of computer technology and human's increased understanding of managerial cognition in recent years have created a renewed research interest in this area (Chen & Lee, 2003). Technology tools have been used to enhance communications and collaboration, accelerate decision-making. However, this study found there is often a mismatch between the way designers make decision and the

way ICT supports it. ICT should play a more active role in facilitating designers' thinking processes and the transfer of tacit knowledge to explicit knowledge.

Several implications can be summarized for ICT support in product design:

- ICT should support the transfer of contextual knowledge
- ICT should support the delivery of relevant knowledge to the right person at the right time
- ICT support should enable the user to access the highly valued knowledge (Cooper, 2003)
- ICT support should be according to the designer's cognitive process (Cooper, 2003)
- Support system should be capable of inferring what the designer is attempting to do in the next step
- It is important to convey precise knowledge to designers

From a cognitive perspective in this study, the future research on ICT support in product design should focus on:

- Understanding designers' activities and processes in product design
- Understanding the relationships among knowledge activities, team activities and decision making activities
- Understanding design space
- Identifying designers' thinking process in the different stages of product design

Some other directions for further research are:

- Finding an industrial case for methodology application and further study
- Comparing KCDM behavior for novice and experienced designers
- Comparing KCDM behavior for virtual team environment and face-to-face environment

The work presented here is only a beginning towards understanding knowledge sharing and knowledge utilization during design. The author hopes the findings in this dissertation will be useful in building knowledge-based collaborative decision making systems. More studies are necessary to validate the methodology in investigating other design scenarios.

Appendix 1 Initial Contact Script

My name is Qiu Yuanfu and I am a PhD student of Nanyang Technological University. We are currently looking for organizations that would be interested in participating in research on team collaboration, decision making and knowledge management of product design.

To be more specific, we are looking for organizations with several product design teams that would be willing to participate in an interview about how to access knowledge effectively during team collaboration, how to make efficient decision supported by knowledge utilization, how to fulfill customers' requirements well and timely.

The project has two components. On the one hand, we would like to survey a large number of product design teams on website to get a better understanding of the problems in the way they experience new product formulation. Meanwhile, we hope that having an interactive session with team members will help us to understand better about the problems and also probe some of the main problems that arise from the survey. This interactive interview would take nearly one hour of team members' time.

All your responses will be treated in confidence and the identities of projects and people will be KEPT confidential and proprietary, only the research team at NTU will see the response. Your remarks and responses will be presented in a sanitized form through coding and modeling. Any verbatim remarks used in the write-up will also be sanitized to protect your identity. In addition, any data that describes a specific product, feature, or release will be shown in an unlabeled form to protect proprietary information.

What are the benefits to your organization?

In return for participating in this project, we will provide a full report on the results of the study. As we will be surveying a wide variety of organizations, we believe that this report will provide valuable benchmarking data.

Appendix 2 Survey on Knowledge-Based Collaborative Decision Making in Product Design

Section 1: Survey in Product Design

This section asks about what are the key factors for designing new products.

1. Knowledge sharing is important for product design
2. Virtual team collaboration is essential for product design
3. Making right and efficient decisions is important for product design
4. Information and communication technology is important for assisting product design
5. The tools I use for product design are easy to use

Section 2: Survey in Individual Decision Making for Product Design

This section asks about what are the key factors that hinder or facilitate knowledge utilization for individual decision making in product design.

6. I have difficulty in getting knowledge about customers needs
7. I have difficulty in getting feedback from customers
8. It is necessary to define decision tasks clearly
9. I have difficulty in sharing my knowledge with others
10. I have difficulty in getting knowledge from my co-workers
11. Assistance from others is helpful for my decision making
12. Reward is useful for facilitating me sharing knowledge
13. I lack innovation in solving problem
14. Decisions are always affected by many uncertain elements
15. It is difficult to know what knowledge is actually relevant to the problem
16. Training is useful for my decision making
17. System support is beneficial to my decision making
18. I have difficulty in solving unexpected problems
19. I do not have knowledge on the relevance of past design projects
20. I struggle with conflicting ideas in design
21. I do not know how to transfer my ideas to actual products
22. Former case studies is useful for current project
23. It is necessary to define decision making process clearly

Section 3: Survey in Team Collaboration for Product Design

This section asks about what are the key factors that hinder or facilitate knowledge sharing within a product design team.

24. Team objectives keep changing
25. Teamwork objectives do not match customers' requirements
26. It is necessary to define teamwork objectives clearly
27. It is necessary for team members to be aware of project risks
28. Difficult to know team members' availability for meetings
29. Team organization is not flexible enough
30. I am not clear about my personal role in team collaboration
31. The organization culture should encourage communication
32. It is necessary to evaluate team performance properly
33. Adequate information about team members' knowledge and expertise is useful
34. Leadership for virtual team collaboration is necessary
35. Team members lack required knowledge for design projects
36. Lack of team innovation
37. System support for virtual communication is necessary
38. Face-to-face discussion with teammates is necessary
39. Evaluation of team knowledge is necessary
40. Lack of trust in teammates' knowledge
41. Do not know how to manage risks and uncertainties
42. Team members have conflicting ideas
43. It is necessary to define team work processes clearly
44. Goal setting will improve team performance

Section 4: Background Information

Company Name	
Gender	☐ Female ☐ Male
Age	☐ 21-30 ☐ 31-40 ☐ 41-50 ☐ Above 50
Job Title	
Highest Education	
How long in average does your typical project last?	_____ Month (s)
Years of experience working in a design team	☐ Less than 1 year ☐ 1-3 years, ☐ 3-5 years ☐ 5 years and more
Which tool/tools do you used in product design? You can choose more than one alternatives.	☐ E-mail ☐ video conference ☐ net meeting ☐ telephone ☐ the world wide web ☐ local area network (LAN) connections ☐ Lotus Notes Data Bases ☐ others (please specify)_____
Please type in your E-mail address	

Appendix 3 Interviews about Knowledge-based Collaborative Decision Making in Product Design

Preamble

Knowledge has become an essential competitive advantage in today's society. One major issue for product design teams is to find creative ways for representing, communicating, transferring, assimilating and integrating knowledge in a competitive manner. This study, which is part of my Ph.D. dissertation requirement, addresses questions of accessing and utilizing knowledge within product design team or between units. What are key factors that hinder or facilitate the effectiveness of knowledge sharing within a product design team? What are key factors that hinder or facilitate knowledge utilization for making efficient decision in product design? The aim of this study is to understand and describe the main problems in accessing and utilizing knowledge for decision making in product design team, and then develop methodology for supporting knowledge access and utilization for product design, which will help ensure higher level of competitive effectiveness and efficiency, higher level of product innovation, decision making and team collaboration.

The study team thanks you for your participation. This conversation will run for approximately one hour. All your responses will be treated in strict confidence and the identities of projects and people will be KEPT confidential and proprietary. Your remarks and responses will be presented in a sanitized form through coding and modeling. Any verbatim remarks used in the write-up will also be sanitized to protect your identity. In addition, any data that describes a specific product feature or release will be shown in an unlabeled form to protect proprietary information. We appreciate your time and input.

Definition

"New Products" here refer to any products deemed new to your company whether or not they are new to the world. New products can range from relatively simple product improvements and line extensions to break-through products. In each phase, problems are supposed to fall into six knowledge activities: Knowledge Identification,

Knowledge Acquisition, Knowledge Transfer, Knowledge Sharing, Knowledge Utilization, and Knowledge Evaluation.

Knowledge Identification: It refers to the identification of what knowledge is required, identification of the difference of different knowledge. To be useful for others, knowledge needs to be documented, structured and related to other knowledge. It is also important to document the knowledge meta-structure, i.e., what kind of knowledge is available, how it is structured, and who can be contacted for advice on a certain subject.

Knowledge Acquisition: It refers to acquiring necessary knowledge from outside. Knowledge to be acquired can be classified as explicit knowledge, such as literature for research and data of customers, and tacit knowledge as experience created and developed from the operation of a process. Knowledge can be acquired within or out of the enterprise and then be input into the knowledge warehouse in the format of electronic document as well as graphics, video clips, sound clips and others.

Knowledge Transfer: It refers to those activities that bring knowledge to the people who need it. It is important that the correct knowledge gets to the right person at the right time. Documented knowledge can be transmitted directly by electronic mail, file transfer, or the distribution of paper documents. Another possibility is the provision of knowledge in a way that users of this knowledge can actively access it, such as in an intranet classroom. Knowledge is mainly transferred through knowledge pushing, electronic publishing, knowledge subscription, education and training.

Knowledge Sharing: It refers to sharing of the available knowledge between employees mutually, between employees and managers, between departments, etc. Knowledge sharing is primarily a knowledge work process that is greatly dependent on the culture of the organization.

Knowledge Utilization: It refers to use the knowledge for carrying out, supporting and improving value-adding activities

Knowledge Evaluation: It refers to activities as assessing, validating, filtering, editing and reorganizing knowledge. Since knowledge can be outdated very quickly, it always needs to be optimised and updated.

Section 1: Background Information

Company	
Your Name	
Job Title	
How long in average does your typical project last?	
Years of experience working in a design team	
Can you tell me your E-mail address?	

Section 2: Questions in Product Design

1. What is your opinion of the role of knowledge management for product design?
2. What is your opinion of the role of team collaboration for product design?
3. What is your opinion of the role of making right and effective decision for product design?
4. What is your opinion of the role of information and communication technology for assisting product design?
5. What are the tools that you have used to share knowledge? What is your opinion of these tools?

Section 3: Questions in Collaborative Decision Making for Product Design

6. What do you think are the main problems for *knowledge identification* in
 - a) **Individual decision making**
-Such as problems in the definition of decision task, difficulty in knowing what knowledge should be required for product design and etc.
 - b) **Team collaboration**
-Such as identification of team objective, project risk and etc.
7. What do you think are the main problems for *knowledge acquisition* in
 - a) **Individual decision making**
-Such as difficulty in acquiring customers' requirements, feedback to products and etc.
 - b) **Team collaboration**
-Such as difficulty in knowing team members' availability for meetings, team members' knowledge expertise and etc.
8. What do you think are the main problems for *knowledge transfer* in

- a) **Individual decision making**
 - Such as difficulty in transferring ideas to actual products, lost of knowledge richness and etc.
 - b) **Team collaboration**
 - Such as problems in team structure, ICT support and etc.
9. What do you think are the main problems for *knowledge sharing* in
- a) **Individual decision making**
 - Such as lack of face-to-face discussion with others, difficulty in sharing knowledge with others in different locations and etc.
 - b) **Team collaboration**
 - Such as enterprise culture, leadership and etc.
10. What do you think are the main problems for *knowledge utilization* in
- a) **Individual decision making**
 - Such as difficulty in knowing how previous design project relate to the current project, problems in making decision collaboratively, not clear about decision making process and etc.
 - b) **Team collaboration**
 - Such as not clear about team work process, personal role in team, uncertainty control and etc.
11. What do you think are the main problems for *knowledge evaluation* in
- a) **Individual decision making**
 - Such as lack of knowledge on the reliability of past design projects, conflict solutions in mind, difficult to know what knowledge is actually useful for decision and etc.
 - b) **Team collaboration**
 - Such as lack of trust in team members' knowledge, conflicting ideas with team members, team performance evaluation and etc.
12. Can you give us some suggestions
- a) On how to make efficient decision for product design
 - b) For improving team collaboration for product design
13. Given your overall experience with product design, can you think of a time/case when knowledge is well shared and utilized in a team for decision making in product design?
14. Do you have any other suggestion for our research?

Appendix 4 Design Task for Experimental Study

Instruction

The study team thanks you for your participation. We are interested in the ways that designers work on design projects. This experiment is being videotaped for later analysis by a number of researchers. I am going to ask you to undertake a short design project. Let me assure you that no commercial advantage will be taken of any design work or ideas that you produce. All your responses will be treated in strict confidence and the identities of companies, projects and people will be KEPT confidential and proprietary. Your remarks and responses will be presented in a sanitized form through coding and modeling. Any verbatim remarks used in the write-up will also be sanitized to protect your identity. In addition, any data that describes a specific product feature, or release will be shown in an unlabeled form to protect proprietary information. We appreciate your time and input.

Because we want to understand what you are thinking during the task, we want you to think aloud continually during the session. This would be as if you are talking to yourself but loud enough for me to hear. The total time available for your design is limited to 6 hours, divided by 3 2-hour sessions. In a moment I will give you a short written design brief for the project.

Drawing materials-paper, pencils, pens and markers are available for your use. Please work as you normally would on such a design project as this. Before I give you the design brief, are there any questions about the experimental study?

If there are no further questions, we will start the session now. I remind you that the maximum time available to you in this session is two hours. I will remind you of the time at 30 minutes and 15 minutes before the end of the session, if you are still working.

Happy working!

Survey on Background Information

Firstly, please take a few moments to fill out some information for classification purposes.

Your Name: _____ **Sex:** _____ **Age:** _____

Education: ☐ Bachelor ☐ Master ☐ PhD ☐ Other **Major:** _____

Company: _____ **Job Title:** _____

How long in average does your typical project last? _____

How many years have you worked in a design team? _____

What are main products that you have designed in the past?

Have you ever worked with your today's team members? If yes, how long?

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

Member name _____: ☐ Yes: _____ year(s) ☐ No

How familiar do you know your today's team members? Please rate your response according to the following categories.

1	2	3	4	5	6	7
Extremely Unfamiliar	Very Unfamiliar	Unfamiliar	Neutral	Familiar	Very Familiar	Extremely Familiar

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Team Member Name: _____ Score: _____

Can you tell me your E-mail address? _____

Design Task: Designing a Portable Entertainment Device

CHFECycling Inc. is a large Singapore firm that produces innovative cycling devices. They have been very successful over the last ten years and are well known internationally for making some of the best vehicles, such as road bicycle, tandem bicycle, unicycle, Mini Scooter, Electric Scooter, Trike etc. However, in the last one and a half years, this company has suffered some setbacks in the market.

CHFEEntertain Inc. is a large Singapore firm that produces innovative entertainment devices. They have been very successful over the last ten years and are well known internationally for making some of the best entertainment devices, such as MP3 player, PDA, Cell Phone etc. However, in the last one and a half years, this company has suffered some setbacks in the market.

As a response, both companies have hired a marketing firm to look for new trends and opportunities for the East Asian market. On the basis of this marketing report, both companies have decided to develop an innovative product for the young adults in East Asian. The device can be any purpose of entertainment, but should be lightweight, portable, innovative and aesthetically exciting.

This idea is particularly interesting for both companies, because the directors of both companies see this as a good opportunity to profit from the East Asian marketing. Your team has been engaged either by CHFEEntertain Inc. or CHFECycling Inc. to design this future entertainment device. Many different types of products already exist in the market. Your company wants your team to propose a “new, original and exciting” product that is not yet available in the market.

You are a valued member of this team. You come with very important knowledge, skills and expertise which are unique to your experience. You will contribute to the design of the product according to the expertise that you have. The product your team designed should be accordable with your company’s background. Your team needs to list down all of your considerations in design, concentrating on:

- Safety
- Ease of use

- Appealing form
- Demonstrating the technical feasibility of the design
- Ensuring that the product stays within a reasonable price range

Your team is suggested to develop this product according to the following three phases:

- 1) Conceptual Design. In this phase, the needs of the target market are identified, alternative product concepts are generated and evaluated, and a single concept is selected for further development and testing. A concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, an analysis of competitive products, and an economic justification of the project. The concept development phase is more critical to the whole process, and demands more coordination among functions than any other.
- 2) System-level Design. This phase defines the product architecture, and divides the product into subsystems and components. The final assembly scheme for the production system is usually defined during this phase as well. The output of this phase is usually a geometric “layout” of the product, a functional specification of each of the product’s subsystems, and a preliminary process flow diagram for the final assembly process.
- 3) Detail Design. Detail Design includes the complete specifications of the geometry, materials, and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers. A process plan is established and tooling is designed for each part to be fabricated within the production system. The output of this phase is the control documentation for the product-the drawing files describing the geometry of each part and its production tooling, the specifications of the purchased parts, and the process plans for the fabrication and assembly of the product.

You may adjust the design phases according to the expertise of your team, but your team is required to finish the design in three 2-hour sessions. Your team is strongly suggested to make full use of your team members’ expertise so that your team can finish all the design of your product. The CEO of CHFECycling Inc. or CHFECycling

Inc. and the directors of the company will evaluate your design based on all the description of your design.

Task 1: Conceptual Design

In this phase, you are suggested to identify the needs of the target market, generate alternative product concepts and evaluate them, and a single concept is selected for further design. Your team is encouraged to generate several ideas and finally choose one promising idea for conceptualization.

Your team also needs to describe your product in a piece of paper (A3 size). Your description is suggested to contain:

- The name of your product
- The annotated sketch of your product explaining your concept design
- The product's features
- Any other important information that you think is important in this phase

Your team has to spend your time wisely for this single 2 hour design.

Task 2: System-level Design

In this phase, basing on the conceptual design in last session, your team needs to define the product architecture, and divide the product into subsystems and components. The final assembly scheme for the production system is usually defined during this phase as well. The output of this phase is usually a geometric “layout” of the product, a functional specification of each of the product's subsystems, and a preliminary process flow diagram for the final assembly process.

Your team also needs to describe your product in this phase in a piece of paper (A3 size). Your description is suggested to contain:

- The annotated sketch of your product explaining your design
- The product's features and specifications
- Any other important information that you think is important in this phase

Your team has to spend your time wisely for this single 2 hour design.

Task 3: Detail Design

In this phase, based on your design in the past two sessions, your design needs to include the complete specifications of the geometry, materials, and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers. A process plan is established and tooling is designed for each part to be fabricated within the production system. The output of this phase is the control documentation for the product-the drawing files describing the geometry of each part and its production tooling, the specifications of the purchased parts, and the process plans for the fabrication and assembly of the product.

Due to time limitation, your team can choose several key parts of your product according to your team's expertise, and design them in detail. Your team also needs to describe your detail design in a piece of paper (A3 size). Your description is suggested to contain:

- The annotated sketch of your whole product explaining your design
- Specifications and detail information of your key parts design
- Any other important information that you think is important in this phase

Your team has to spend your time wisely for this single 2 hour design.

HAPPY WORKING!!

Appendix 5 Survey on the Knowledge in Product Design

The objective of this survey is to identify your consideration of the following knowledge/activity in design process. Please rank the importance of the following Knowledge/Activities in your design with the most appropriate response.

Knowledge/Activities	Knowledge/Activities
1. Requirements of customers	2. Performance attributes and criteria
3. Requirements of the task assigned	4. Available new technology
5. Consideration of different customers	6. Re-use existing suitable cases for reference
7. The influence of culture difference on product	8. Consideration of the form of possible function models
9. The impact of function on performance	10. Models of product functionality
11. The impact of function on cost	12. Design Standards
13. Safety requirements	14. Modification of objects
15. Information about the available Off-the-shelf components	16. Materials for product
17. Relative market prototypes/mockups	18. Performance data of product
19. Quality requirements	20. Prototyping tools for product design
21. Failed idea of past design	22. Knowledge of general product design process
23. Experience in design	24. Product-related data collection plan
25. Creativity	26. Re-use procedures and conditions from prior study
27. Discussion with team members	28. Case reasoning process
29. Input/output representations ability	30. Modification of procedures and conditions
31. Predictions of the Product's Model	32. Retrieve and adapt existing model with appropriate tools
33. Simulation of conceptual functions in mind	34. Viewgraphs of the design state
35. Simulation of design components in mind	36. Problem solving process
37. Alternative solutions selection	38. Past design forming process
39. Adoption of a form	40. Performance measurement of the product

Appendix 6 Survey on Knowledge-based Collaborative Decision Making in Product Design

This survey asks about what are the key factors that hinder or facilitate knowledge access and utilization within your product design process.

1. Team objectives keep changing
2. It is necessary for team members to be aware of project risks
3. It is necessary to define teamwork objectives clearly
4. Lack of trust in teammates' knowledge
5. Adequate information about team members' knowledge and expertise is useful
6. I am not clear about my personal role in team collaboration
7. Team members lack required knowledge for design projects
8. I prefer to obtain knowledge from my familiar team members
9. Former case studies is useful for current project
10. It is necessary to define product development process clearly
11. I have difficulty in getting knowledge about customers needs
12. I have difficulty in sharing knowledge with others
13. Different knowledge is needed in different design phases
14. Team lacks innovation in solving problems
15. Decisions are always affected by many uncertain elements
16. It is difficult to know what knowledge is actually relevant to the problem
17. I do not know how to transfer my ideas to actual products
18. Sketching is helpful in transferring my knowledge to team members
19. It is necessary to understand the design situation for my decision making
20. Leadership for team collaboration is necessary
21. Goal setting will improve team performance
22. Team members have conflicting ideas
23. Time constraint decreases my performance in making decisions
24. The differences of team members' knowledge backgrounds contribute to team's decision making
25. It is necessary to have tradeoff with team members
26. My orientation to a solution is influenced by expertise

Appendix 7 Interactive Interview in Different Product Design Phases

1. What is your consideration of the following different knowledge class in product design in this phase?
 - Market knowledge
 - Human knowledge
 - Technology knowledge
 - Procedure knowledge
2. What is your consideration of the product characteristics during your design Process in this phase?

– Geometry	– Material	– Position
– Shape/Size	– Quality	– Linkage
– Function	– Kinetics	– Assembly
– Manufacturing	– Ergonomics	– Esthetics
– Maintenance	– Costs	– Safety
– Market	– Miscellaneous	
3. What is your opinion of the following knowledge activities for product design in this phase (the frequency and the way you behave)?
 - Knowledge generation
 - Knowledge sharing
 - Knowledge evaluation
 - Knowledge utilization
4. What is your opinion of team collaboration for product design in this phase?
 - Common purpose
 - Team communication
 - Team structure (Clear roles/ Accepted leadership/ Solid relationships)
 - Effective process
5. What is your opinion the following issues in decision making for product design in this phase (the frequency and the way you behave)?
 - Objective

- Alternative
 - Criteria
 - Decision
 - Outcome
6. What is your perception of the design situation and progress during your product design in this phase?
 7. What is your opinion of the difference among different design phases, namely conceptual design, system-level design, and detail design? (for the third session only)
 - Knowledge, description, level of association of knowledge
 - Knowledge activities, team collaboration, decision making
 - Level of abstraction & aggregation in product design
 8. What are the tools that you have used to share knowledge? What is your opinion of these tools? (for the third session only)
 9. Can you give us some suggestions (for the third session only)
 - How to better manage knowledge in product design?
 - How to improve team collaboration in product design?
 - How to make efficient decision in product design?
 - How to use information and communication technology to support product design if you are under virtual environment?

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