Roles of Perception in Engineering Design – A Theoretical Foundation to Improve Designer's Performance

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Abstract

Roles of Perception in Engineering Design – A Theoretical Foundation to Improve Designer's Performance

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Engineering design is a complex decision-making process which frames the transition from an engineering problem to a final product, to meet a set of requirements. During this process, perception is inevitably involved. Perception, a term originated from psychology, referring to a process where a person arrives at an interpretation of his/her sensory experience about the surroundings, has been involved in a broad scope in engineering design, e.g., understanding a design problem, comprehending customers requirements, conceptualizing design thoughts, organizing and managing resources, and evaluating alternative solutions. To study the engineering process from the perception's perspective, a theoretical model has been proposed. In this model, workload, skill, knowledge, and affect are chosen as major factors. Based on the model and the Environment-Based Design methodology, methods are proposed to quantify designer's perception and performance at conceptual design stage. Experimental studies have been conducted to validate the proposed model. As a result, the model serves well as a phase-based quantification tool for designer's perception and performance. In addition, a significant positive correlation has been found between one's perception and performance. Furthermore, the model implies a foundation to improve one's performance for engineering design.

Dedication

I dedicate my humble effort to

my parents, Weiguo Tan & Fanzhi Zeng,

and

my wife, Qian Xiao,

for their unconditional love and continuous support.

Acknowledgments

I am honored to express my sincere gratitude to my academic supervisor, Dr. Yong Zeng, for his continuous support, guidance, constant patience and inspiration throughout my graduate studies. Without his encouragement and support, I would not have finished my Ph.D. program.

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Chapter 1

Introduction

1.1 Background

Engineering design includes, but not limited to, several major activities (Cross, 2008; Dieter & Schmidt, 2012; Pahl, Beitz, Feldhusen, & Grote, 2007; Ullman, 2009): define the problem, do background research, specify requirements, propose conceptual solutions, conduct technical review, develop and prototype solutions, communicate results, and test and refine solutions. Those activities require designers to retrieve knowledge in their long-term and working memory, and apply their possessed skills, to get and organize related information/data, and then make sense of the complex information/data at an abstract and conceptual level (Bilda & Gero, 2007; Liikkanen & Perttula, 2009; Ware, 2013). This fits into the high level perception domain (Chalmers, French, & Hofstadter, 1992; Henderson & Hollingworth, 1999).

Perception, a term originated from psychology, is a process where a person arrives at an interpretation of his/her sensory experience about the surroundings (Guenther, 1997). It has been recognized that perception goes on at many levels (Chalmers et al., 1992). Perception is yet generally divided into low and high levels. Low level perception is concerned with extraction of physical properties such as size, color, orientation (Henderson & Hollingworth, 1999), which acts as the foundation for high level perception. High level perception happens at the level of processing where "concepts" begin to play an important role (Chalmers et al., 1992). Perceptions act as filters, thus preventing us from being overwhelmed by all of the noise (stimuli) around us (Kenyon & Sen, 2015). Perception plays a fundamental role for a human being to understand and to interact with his/her environment.

In the existing literature of perception in engineering design, efforts were made from the psychology's perspective. Researchers focus on how to organize and interpret the information (Ware, 2013), to explore solution spaces, and finally to represent them into a meaningful artifact. Perception is involved in a broad scope of problems in engineering design, e.g., understanding a design problem, comprehending customer requirements, conceptualizing design thoughts, organizing and managing resources, and evaluating alternative solutions. Understanding the role of designer's perception in engineering design is undoubtedly beneficial to improve a designer's performance.

1.2 The Research Problems

In order to understand the impact of perception on desinger's performance in conceptual design, we must answer the following questions:

(1). How to evaluate designer's performance in engineering design?

(2). How to evaluate designer's perception in engineering design?

(3). How are the perception and the performance correlated?

(4). How to improve performance through perception?

Designer's performance refers to the quality of his execution of work (Neal Jr., 2014). To assess a designer's performance, his/her design solution is best and most commonly used manifestation. Therefore, the solution evaluation attracts a great attention. Many methodologies/techniques/theories have been proposed as guidelines for solution evaluation. Examples include Feasibility Judgment (Tversky & Kahneman, 1983), GO/NO-GO Screening (Carbonell-Foulquié, Munuera-Alemán, & Rodrıguez-Escudero, 2004; Han & Diekmann, 2001), Basic Decision Matrix / Weighted Decision Matrix / Advanced Decision Matrix (Triantaphyllou, 2000; Tzeng & Huang, 2011), Analytical Hierarchy Process (AHP) (Handfield, Walton, Sroufe, & Melnyk, 2002; Saaty, 1999, 2008), Quality Function Deployment (QFD) (Akao, 2004), Criteria for Accrediting Engineering Technology Programs (ABET, 2014), and Axiomatic Design (Suh, 2001). A major problem for those methods is that they depend heavily on engineering characteristics, which are mostly numeric engineering parameters. However, conceptual design solutions are more of concept abstractions, e.g., sketches for mechanical engineering, data abstraction and procedural abstraction for software engineering (Liskov & Guttag, 1986). Those methods are not suitable to evaluate conceptual design solutions.

The difficulty in evaluating a designer's perception lies in that the psychological factors of perception are somewhat intangible and are not easy to have numerical indicators, compared to engineering parameters. There have been previous studies in perception evaluation from other domains through survey: assessment of young children's self-perceptions of their school adjustment (Measelle, Ablow, Cowan, & Cowan, 1998), assessment of student perception on teaching effectiveness (Y. Chen & Hoshower, 2003; Santagata & Yeh, 2016), evaluation of customer perception for the quality of service (QoS) (L. Liu, Zhou, & Song, 2008), and aesthetics perception (Pelowski & Akiba, 2011). The problems with survey-based evaluation methods are (1) A good survey should be well designed to generate meaningful results. And it is already "contaminated" by the perception of the survey designer. (2) The results reflect surveyees' perception on the solution. It is an inappropriate indicator of a designer's perception. (3) A conceptual solution at early design stage is a subjective choice shaped by the designer's knowledge and experience. A survey is not applicable in such a circumstance. Although there has been previous work (Kenyon & Sen, 2015; Ware, 2013) qualitatively outlined the different psychological perspectives on designer's perception in a design process, not a general and quantitative method was proposed to quantify designer's perception. There is an evident demand of an evaluation system for designer's perception, especially in the conceptual design phase.

Few previous related research studied the relation between perception and performance through questionnaire/survey or similar from. For example, R. Johnston and Heinke (1998) explored the relationship between service performance and customer's perceptions of that service performance. Juslin (2000) studied the utilization of acoustic cues in communication of emotions in music performance, in order to align the performer's intention to listener's perception. Papamitsiou and Economides (2014) studied relation between students' perception of performance and their actual performance. Athanasiou et al. (2016) investigated professors' self-perception of mentoring skills and their academic performance through survey. All those studies preserved the aforementioned survey-type issues. And, they focused on the correlation of A's performance and B's perception. This is not the case for the presented research. In this thesis, we interested in the correlation of A's performance and A's perception. Athanasiou et al. (2016) made a step into this direction, but through survey. Therefore, the previous research can not be applied to our case. Improving one's performance through his own perception has not been studies in the literature.

Regarding the relation between designer's perception and performance, a major hypothesis is to be validated:

> "*A designer who has a good perception of a design problem tends to deliver a good performance.*"

1.3 Objectives and Contributions

The main objective of this thesis is "study the roles of perception in engineering design, in order to improve designer's performance in conceptual design phase". To achieve this main objective, three sub-objectives are derived: (1) to develop a method to quantify designer's performance at the conceptual design phase; (2) to propose a theoretical model for evaluation of designer's perception at the conceptual phase; (3) to conduct experimental study to validate the proposed hypothesis.

In this research, methods have been derived from the Environment-Based Design methodology (EBD) (Zeng, 2011, 2015) to quantify designer's performance and perception, respectively. In addition, a theoretical model is derived from the inverse U curve and the stress formula (Nguyen & Zeng, 2012) to model to roles of perception in engineering design. The theoretical model is a reflection and abstraction of the engineering applications presented in Chapter 5. It comes from engineering applications, and goes back to support engineering design. Furthermore, the proposed methods and model have been validated by the experiment. There is a significant positive correlation between perception and performance.

This research makes both theoretical and application contributions. The theoretical ones are outlined as:

- A theoretical model about the role of perception in engineering design;

- A method to evaluate designer's perception in conceptual design;
- A method to evaluate designer's performance;
- Statistical validation of positive correlation between designer's perception and performance.

Whereas, the application contributions are:

- Reverse design approach based on EBD, which has been applied to an Engineering Design Education program as a foundation;
- Software design using EBD;
- Medical device design using EBD.

1.4 Thesis Organization

This thesis is organized as follows: Chapter 2 presents related literature review. The proposed theoretical model of perception in engineering design and the methods to quantify designer's perception and performance are elaborated in Chapter 3. Experimental evidences to the model are addressed in Chapter 4. Chapter 5 provides three case studies, from which the proposed model is reflected and abstracted. Chapter 6 concludes the thesis and proposes future work.

Chapter 2

Literature Review

Engineering is a broad field that is divided into various disciplines and sub-disciplines. The multidisciplinary nature of modern engineering and complexity of design brought significant challenges to designers/engineers (referred to as "designer(s)" hereafter).

2.1 Engineering Design – Multiple Perspectives

An engineering design process involves three components: an engineering design problem, a designer, and solutions. An engineering design problem is normally presented as a form of problem statement to a designer by someone else, the client or supervisor (Cross, 2008). It can be also represented by a set of requirements (Pahl et al., 2007). A designer refers to a person who is involved in an engineering problem solving process, and is developing solutions to the problem. Solutions are the results of a design process to solve the engineering problem.

Among many definitions given to engineering design, ABET (Accreditation Board for Engineering and Technology) gives a comprehensive one: "Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs (Atman, Chimka, Bursic, & Nachtmann, 1999)". The definition itself provides some basics to engineering design: component, process, desired needs, decision-making, knowledge, and resources. Research has thus been made from different perspectives around these basics.

2.1.1 Models of Design Process

The objective of engineering design is to establish a well-planed process, specifications, and other related information needed to realize products that meet customer requirements. Generally, there are two types of model for design: descriptive model and prescriptive model. A descriptive model describes how things are generally done. It presents a general overview of a design process without going into many details (Fosmire & Radcliffe, 2013). A descriptive model helps a person to understand the overall picture. According to literature (Dieter & Schmidt, 2012; Mastinu et al., 2009; Pahl et al., 2007; Ullman, 2009), there are four stages to describe a design process in general:

- **Problem analysis** is a process for a designer to use analytic skills or tools to increase his understanding of an ill-defined problem at current situation. In this stage, the designer need to (1) clarify objectives; (2) clarify the known and unknown concepts, and lay out the relations among them; (3) get user requirements; (4) identify constraints. That is, in a simpler way, searching related information the problem. The information may be in a wide variety of formats: text, drawings, sketches, images, physical artifacts, prototypes or mock-ups, or computer models and/or simulations (Fosmire & Radcliffe, 2013).

- **Conceptual design** determines the principles of a solution. With the given information from the problem analysis, a designer needs to (1) break down the problem into sub-problems; (2) establish function structures; (3) search for appropriate working solution principles; (4) combine and firm up the concept variants (Fosmire & Radcliffe, 2013; Mastinu et al., 2009). As result, a basic solution or a set of temporary solutions are generated through the elaboration of solution principles.

- **Embodiment design** is a process which starts from the structure or concept of a technical product, to develop a set of solutions for sub-problems. The solutions are then evaluated against the technical and economic criteria, and a preferred solution is chosen as the product form for next stage.

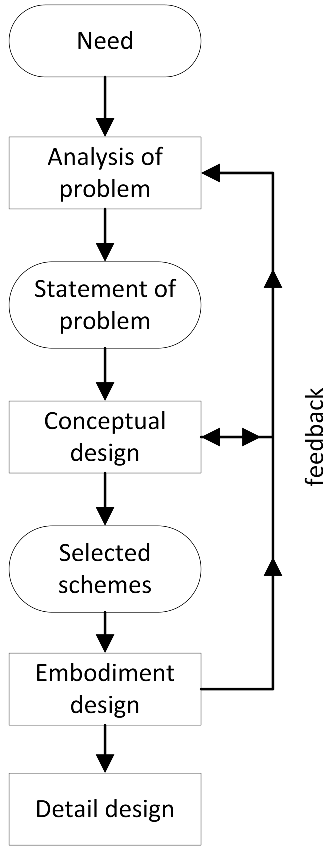

Figure 2.1: Descriptive model of design. Modified from (French, 1971)

- **Detailed design** is a process which completes the embodiment of the product, with final instructions about the layout, forms, dimensions and properties of all individual components, the selection of materials and/or tools, operating procedures and costs (Pahl et al., 2007).

A wildly accepted descriptive model of design process is presented by French (1971). The model is shown in Figure 2.1.

Different from the descriptive model, a prescriptive model tells a designer exactly how to do the work. A prescriptive model example is illustrated as Figure 2.2.

The above classification of engineering design is rather general and logical. Instead of logical classification, engineering design can be seen as a problem-solving process (Dieter & Schmidt, 2012). Therefore, the activities involved in problem-solving can be used to characterize an engineering design process. The following are some major ones (Dieter & Schmidt, 2012; Kanematsu

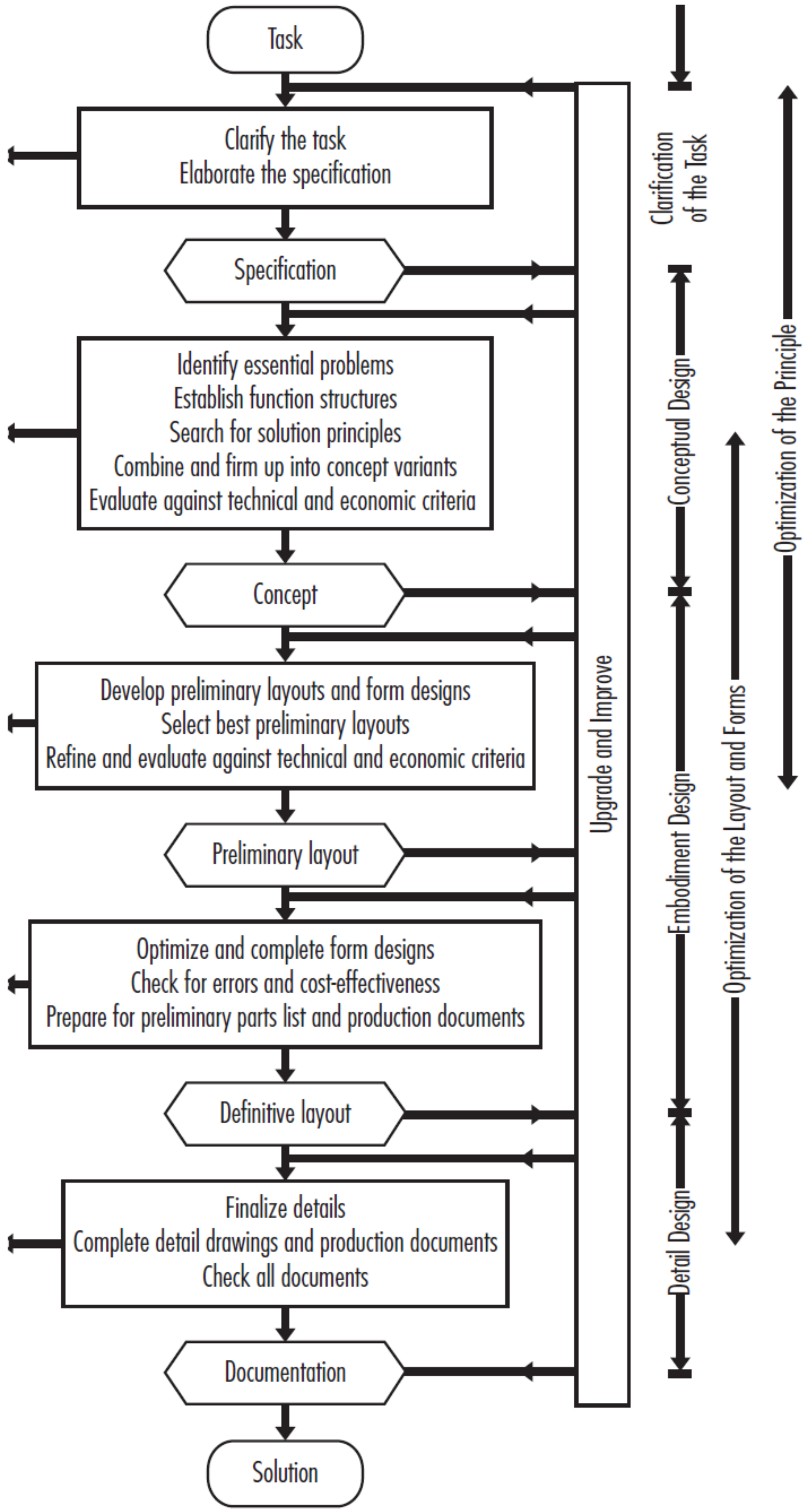

Figure 2.2: Prescriptive model of design. Modified from (Fosmire & Radcliffe, 2013; Mastinu et al., 2009)

& Barry, 2016b):

(1). Identify the Problem: Select or determine a problem that needs to be solved. It can be written in the form of a question.

(2). Collect Data: Data are collected (to solve the problem) by making measurements and observations and by searching the literature.

(3). Identify Design Requirements: In creating a design to solve the problem, one must incorporate the design requirements. For example, if you were to design a new house, several design requirements would be the size and shape of the house.

(4). Identify Design Limits: What are the limitations to your design? For example if you are building a new house, several design limits are the amount of money and resources available.

(5). Generate Possible Solutions: For example if you were asked to design a new ladder, possible solutions could be a rope ladder, a step ladder, or an extension ladder.

(6). Evaluate the Alternatives: Look over the alternatives (possible solutions to the problem) to determine which one is best for solving the problem.

(7). Select the Best Approach: After evaluating the alternatives (possible solutions), select the best approach for solving the problem.

(8). Communicate the Selected Design: The selected design may be shared with others by using sketches, words, a descriptive procedure, etc.

(9). Implement the Design: Use the design to make the product, etc.

(10). Test the Product: For example, if you designed and made a paper airplane to fly a great distance, then test it.

(11). Modify the Design: If you are not satisfied with the product, then modify the design to improve it.

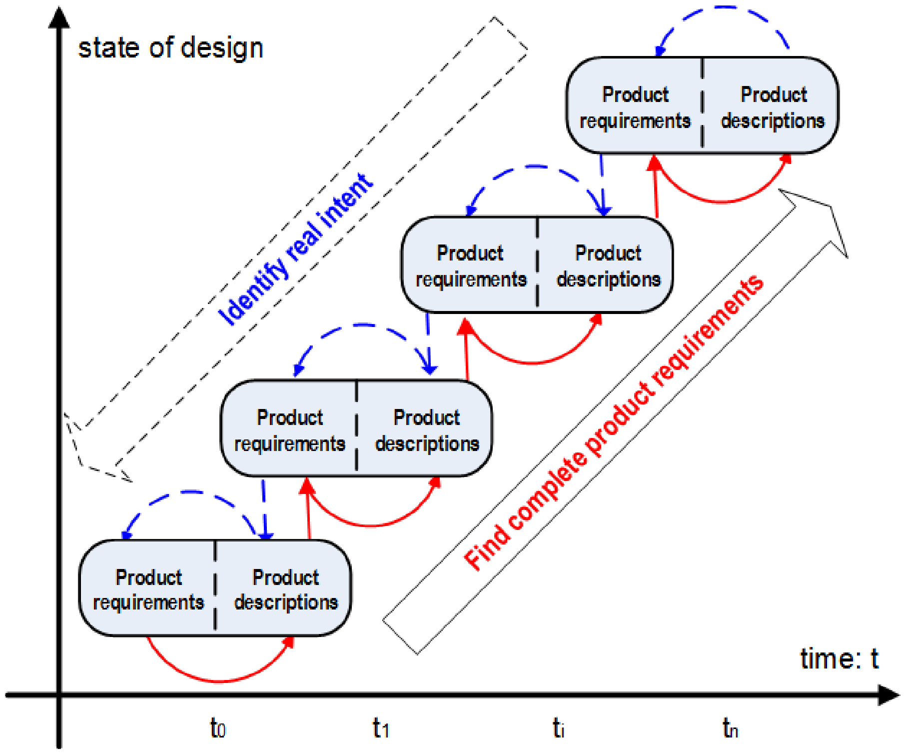

Figure 2.3: Evolutions of a product design. Adopted from (Z. Chen et al., 2007; Z. Y. Chen, 2006; Zeng, 2011).

2.1.2 The Nature of Design Process

Though the classification above frames the engineering design process, it does not reflect the nature of a design process. The design process is not only a loop evolution: product design ⇒ manufacture ⇒ product design (Suh, 2001), but also a recursive process within its process (Zeng & Cheng, 1991; Zeng & Gu, 1999). Zeng and Cheng (1991) proposed that a design process is a recursive process, which means that the design problem will be shaped by the partial solution provided from previous stage. Meanwhile, the solution will be shaped by the refined design problem. Dorst and Cross (2001) stated the same concept of " co-evolution of problem–solution". Cross (2008) stated that proposing solutions is a means of understanding the problem. Many constraints and criteria emerge as a result of evaluating solution proposals. Therefore, a design process is an evolution process for both solution proposals and problem refinements (Cross, 2008). The process can be modeled as Figure 2.3. The ultimate goal of design is to find complete product requirements, or, the desire needs., and to satisfy them.

However, in most cases, especially for an open-ended problem, the desired needs are not comprehensively stated in a design statement. A designer must interpret the design problem from highly abstract level into detailed engineering parameters so that the engineering sciences are applied to convert resources optimally to the final product. The whole design process is a negotiation between problem and solution (Lawson, 2005), a recursive processing of sharping each other (Lawson, 2005; Zeng, 2011). It (1) is endless; (2) is no infallibly correct process; (3) involves finding as well as solving problems; (4) inevitably involves subjective value judgment; (5) is a prescriptive activity (American Institute of Architects, 2008).

2.1.3 Designers – Experts and Novices

Many design researchers have attempted to characterize design through different activities which a designer exhibits, such as problem framing, solution generation, and evaluating alternative solutions. For example, Sim and Duffy (2003) presented a set of consistent and coherent definitions of these activities.

Because of the multidisciplinary nature of modern engineering and the complexity of design, an engineering design process may involve hundreds of resources (e.g., designers, collaborator, suppliers, manufactures, analysts, computers, software systems, and procedures) and thousands of design activities (Kusiak & Park, 1990). Therefore, experts are demanded from each industry, as experts solve complex problems considerably faster and more accurately than novices do (Larkin, McDermott, Simon, & Simon, 1980). Much research has been done to compare expert's and novice's performance in different domains (Atman et al., 2007; Barfield, 1986; Carter, Cushing, Sabers, Stein, & Berliner, 1988; Elio & Scharf, 1990; Larkin et al., 1980; Livingston & Borko, 1989), in order to model and/or shorten a novice-to-expert transition. It is reported that experts tend to treat the cause of the problem rather than fixing the symptoms (Lawson, 2005). Barfield (1986) concluded that experts differ from non-experts in how they acquire knowledge, solve problems and process information in software engineering. Carter et al. (1988) found that, in education, experts appeared to possess comparatively richer schema for scribing meaning. In engineering design, Atman et al. (2007) observed that, compared to students (novice designers), experts spent significantly more time on the task overall and in each stage of engineering design, including significantly more time on problem scoping. The experts also gathered significantly more information that covers more categories. Ting (2014) found that (1) students tended to use depth-first decomposition, (2) students spent less cognitive effort when considering the problem as a whole and interactions between subsystems than engineer experts. and (3) experts tended to use breadth-first decomposition in engineering design, meaning that students used less problem decomposition and problem recomposition (synthesis) than engineer experts, and spent more cognitive effort when considering details of subsystems. Shanteau (1992) assumed that designer's competence depends on five components: (1) a sufficient knowledge of the domain, (2) the psychological traits associated with experts, (3) the cognitive skills necessary to make tough decisions, (4) the ability to use appropriate decision strategies, and (5) a task with suitable characteristics.

As a summary, experts spend more time in problem scoping/decomposition and information gathering, and tend to formalize design problems in a hierarchy fashion.

2.2 The Psychology of Perception

Since design is a decision-making process, perception is inevitably involved. Perception is a process where a person selects, organizes, identifies, and interprets the sensory information he receives in order to understand his environment (Kenyon & Sen, 2015, Chapter 5). Perceptions act as filters, thus preventing us from being overwhelmed by all of the noise (stimuli) around us. Perceptions can be shaped by learning, memory, and expectations. Guenther (1997) defined perception as "the process by which we arrive at an interpretation of sensory experience". It is indeed a sequence of complex and hidden operations taking place in the brain, the cerebral cortex, specifically. Now, we can clearly say that the process of perception is embedded in a design process, as it is the most fundamental process happens to every designing activity.

It has been recognized that perception goes on at many levels (Chalmers et al., 1992). It is generally accepted that there are three stages in a perceptual processing.

Stage 1: Parallel processing to extract low-level properties of our scene, called "attended stimulus" in (Kenyon & Sen, 2015)

This stage is a bottom-up and data-driven process.

Stage 2: Pattern Perception, called "transduction" in (Kenyon & Sen, 2015)

This stage is a slow serial processing process. It involves both working memory and long-term memory. And, it is a combination of bottom-up feature processing and top-down attentional mechanisms.

Stage 3: Sequential goal-directed processing, called "interpretation" in (Kenyon & Sen, 2015)

This stage sites at the highest level of perception. Objects are held in working memory by the demands of active attention.

The three-stage model of perception is the basis for understanding. Figure 2.4 gives an overview of the three-stage perception processing, using visual perception as an example.

Perception can be divided into low and high levels for simplification. Low level perception (stage 1 and stage 2 in the three-stage model) is concerned with extraction of physical properties such as size, color and orientation (Henderson & Hollingworth, 1999), which acts as the foundation for high level perception. High level perception (stage 3 in the three-stage model) happens at the level of processing, where "concepts" begin to play an important role (Chalmers et al., 1992). Through high-level perception, chaotic environmental stimuli are organized into mental representations which are meaningful "concepts".

Perceptions can be shaped by learning, memory, and expectations. A huge amount of work has been done to understand human perceptions from different perspectives (Baylis, Gore, & Rodriguez, 2001; L. Chen, 2005; Crick & Koch, 1995; Doeller, Barry, & Burgess, 2010; A. Johnston & Wright, 1983; Kellman & Shipley, 1991; Kenyon & Sen, 2015; Kolers, 1963; Marr, 1982; Mather, 2006; Murakami & Cavanagh, 1998; Sharpee et al., 2006), e.g., psychology, phisiology and artificail intelligence.

2.3 Perception in Engineering Design

It is reported that all humans have the same cognitive, or problem-solving, structure (Ullman, 2009). Efforts have been made to capture the basic cognitive activities. The hierarchy classification of cognitive domain activities from the revised Bloom's Taxonomy, shown in Figure 2.5, is the

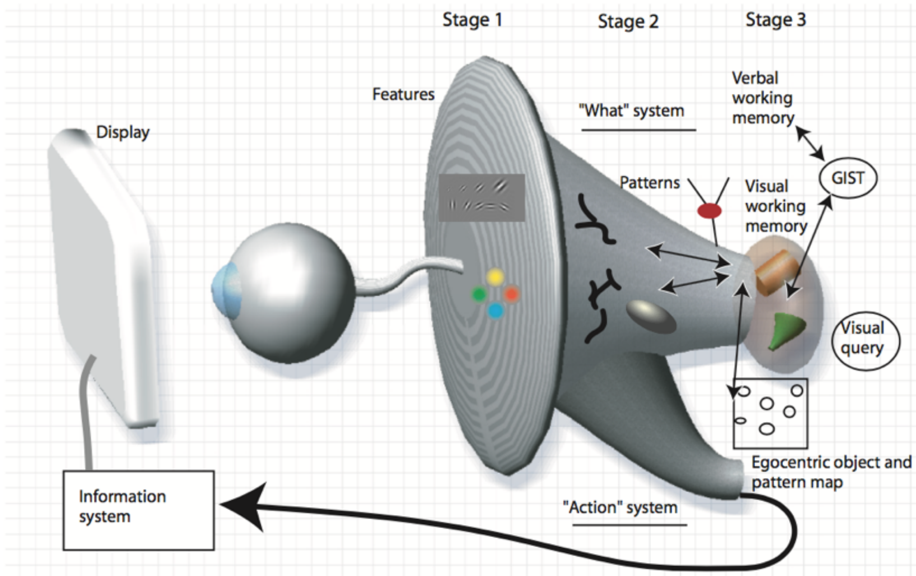

Figure 2.4: The tree-stage perception process – a visual perception example. Adopted from (Ware, 2013)

most widely accepted one. The cognitive domain is characterized by intellectual abilities and skills, from simple recognition of facts, through increasingly more complex and abstract levels of mental operations. From highest to lowest, the six levels are:

- Creating: Putting elements together to form a coherent or functional whole; reorganize elements into a new pattern or structure (generate, plan, produce, establish, invent, form, develop, formulate).

- Evaluating: Making judgments based on criteria and standards (appraise, argue, defend, judge, select, support, value, evaluate).

- Analyzing: Breaking down a problem, concept, system, or information into their constituent parts; distinguishing among pieces or components and describing their purposes and relationships (appraise, compare, contrast, criticize, differentiate, discriminate, distinguish, examine, experiment, question, test.).

- Applying: Implementing or using knowledge in a concrete way in a given situation to solve a problem, make a decision, or answer a question (choose, demonstrate, dramatize, employ,

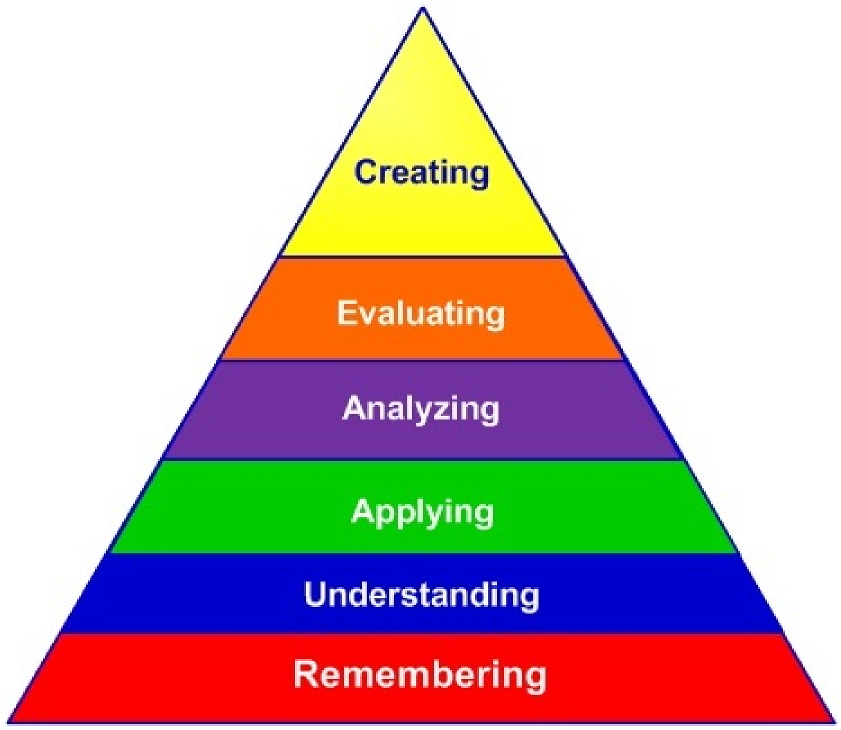

Figure 2.5: The revised Bloom's model captures activities in cognitive domain.

illustrate, interpret, operate, schedule, sketch, solve, use, write.).

- Understanding: Constructing meaning from instructional messages, including verbal, written, and graphical communication (classify, describe, discuss, explain, identify, locate, recognize, report, select, translate, paraphrase).

- Remembering: Retrieving relevant knowledge from long-term memory, through recognition or recall (define, duplicate, list, memorize, recall, repeat, reproduce state).

Though the revised Bloom's Taxonomy was proposed for education purpose, it provides us with a common language that we can use to articulate a designer's knowledge and skills in an engineering process.

In an engineering design process, the best form to preserve and reflect a designer's initial (sub-)solution is by sketching. Others have documented the way that sketching supports design (Cardella, Atman, & Adams, 2006). This is also true for communication purpose between designers. Drawing

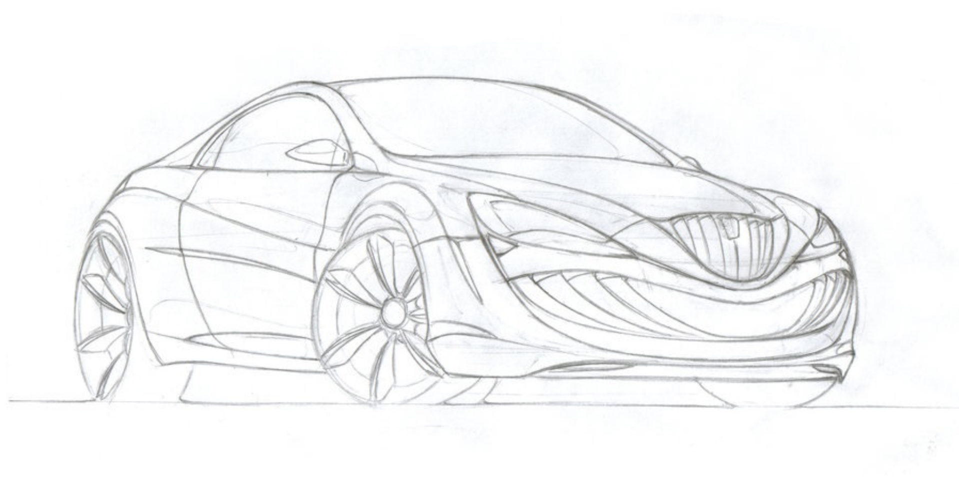

Figure 2.6: Sketch of a concept car by Miletić Design.

is also used to refer to the sketching in previous work (Cross, 2008). However, there are quit differences. “Sketching” generally means freehand drawing with one’s hand. In contrast, “drawing” means using drawing instruments, for example CAD software, to bring precision to the drawings. Therefore, sketching happens in conceptual design stage, whereas drawing happens in embodiment and detail design stages. Due to its freedom, sketching is wildly used in engineering design. Figure 2.6 and 2.7 show a sketching of a concept car and a CAD drawing examples, respectively. Sketching and drawing are not the only forms used to convey information or knowledge in a design process. Natural language, images and equations are other three mostly used forms.

Natural language provides us with the most developed and widely used symbol system available (Ware, 2013). We were trained intensively from early age. In comparison, images and equations are more abstract and effective in representing information and knowledge. We are not similarly experts in understanding them in the same level. Eventually, image and equations can be represented in natural language. Ware (2013) suggested with evidence that designers should use those forms together whenever possible to increase understanding.

Come back to the engineering design process, a problem description is often presented using natural language, in written or spoken. The description is mostly ill-defined or ill-structured. Therefore, in order for designers to solve problems creatively, they must understand the problem well and

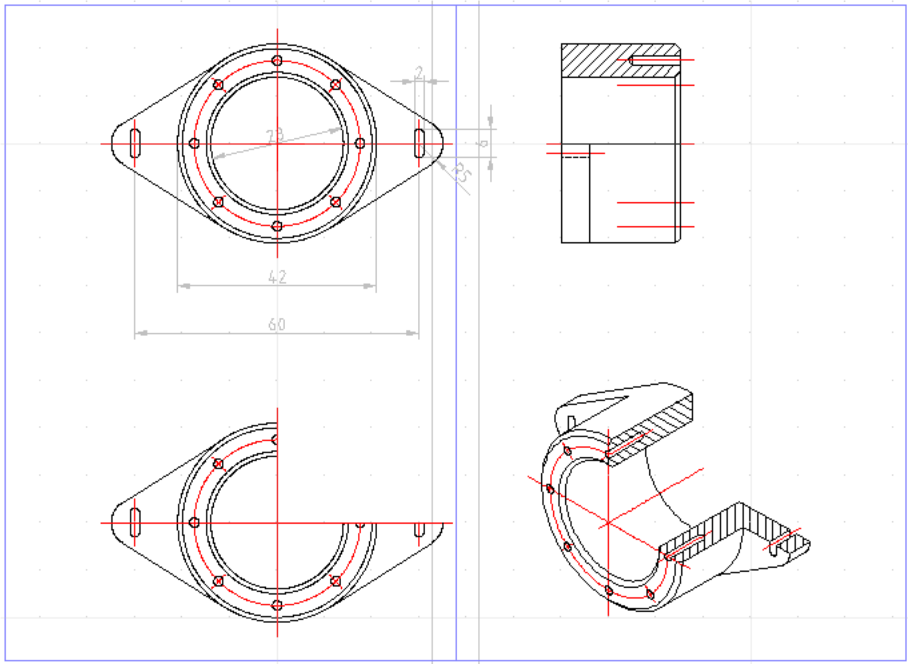

Figure 2.7: A CAD drawing example.

then work at the synthesis level (where one creates ideas, etc.) or the evaluation level (where one makes value judgments, etc.) to deliver a solution (Kanematsu & Barry, 2016a). In addition, designers have to make assumptions, and to make critical decisions on the basis of these assumptions and incomplete information. Those require high level perception.

Perception is so fundamental in an engineering design process, evaluating it becomes a topic. The difficulty in evaluating a designer's perception lies in that the psychological factors of perception are somewhat intangible and are not easy to have numerical indicators, compared to engineering parameters. There have been previous studies in perception evaluation from other domains through survey or similar forms: assessment of young children's self-perceptions of their school adjustment (Measelle et al., 1998), assessment of student perception on teaching effectiveness (Y. Chen & Hoshower, 2003; Santagata & Yeh, 2016), evaluation of customer perception for the quality of service (QoS) (L. Liu et al., 2008), and evaluation of aesthetics perception (Pelowski & Akiba, 2011). The problems with the survey-based evaluation methods are (1) A good survey should be well designed to generate meaningful results. And it is already "contaminated" by the perception of the survey designer. (2) The results reflect surveyees' perception on the solution. It is an inappropriate indicator of a designer's perception. (3) A conceptual solution at early design stage is a subjective choice shaped by the designer's knowledge and experience. A survey is not applicable in such a circumstance. Although there has been previous work (Kenyon & Sen, 2015; Ware, 2013) qualitatively outlined the different psychology perspectives on designer's perception in a design process, not a general and quantitative method was proposed to quantify designer's perception. There is an evident demand of an evaluation system for designer's perception, especially in the conceptual design phase.

Evaluating a designer's perception might be one perspective to assess his/her performance. There is another perspective – his/her design solution, the best and most commonly used manifestation. Therefore, solution evaluation attracts much attention. Many methodologies/techniques/theories have been proposed as guidelines for solution evaluation. Examples include Feasibility Judgment (Tversky & Kahneman, 1983), GO/NO-GO Screening (Carbonell-Foulquié et al., 2004; Han & Diekmann, 2001), Basic Decision Matrix / Weighted Decision Matrix / Advanced Decision Matrix (Triantaphyllou, 2000; Tzeng & Huang, 2011), Analytical Hierarchy Process (AHP) (Handfield et al., 2002; Saaty, 1999, 2008), Quality Function Deployment (QFD) (Akao, 2004), Criteria for Accrediting Engineering Technology Programs (ABET, 2014), Axiomatic Design (Suh, 2001), performance rating by experts (Borman, 1977; Sulsky & Balzer, 1988), and their derivatives. A major problem for those methods is that they depend heavily on engineering characteristics, which are mostly engineering parameters. However, conceptual design solutions are more of concept abstractions, e.g., sketches for mechanical engineering, data abstraction and procedural abstraction for software engineering (Liskov & Guttag, 1986). They are so abstractive and seemly intangible. Those methods are not suitable to evaluate conceptual design solutions. A new quantification system is needed for conceptual design solutions, as any mistake or inappropriate conceptual solution chosen at the early design stage may be inherited by the next stage, and cannot be eliminated in production process (Derelöv, 2008).

The needs for evaluation systems for both perception evaluation and conceptual solution evaluation became the sub-objectives for this research.

Chapter 3

The Proposed Model

3.1 The Theoretical Model

The proposed model is based on the theoretical model of design creativity proposed by Nguyen and Zeng (2012), which takes the following two postulates as the foundation to study:

- Postulate 1: Design reasoning follows a nonlinear dynamics, which may become chaotic.
- Postulate 2: Design creativity is related to a designer's mental stress through an inverse U shaped curve (see Figure 3.1).

The first postulate addresses the relation between evolving design states. Designing is formulated as an environment evolution process where an earlier design solution becomes a part of the environment for the current design stage. This environment evolution implies a nonlinear chaotic

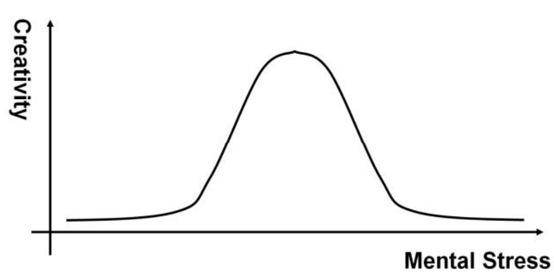

Figure 3.1: The inverse U curve relation between mental stress and design creativity.

dynamics, in which design problem, design solution, and design knowledge will change in a recursive and interdependent manner (Nguyen & Zeng, 2012; Zeng & Gu, 1999). A great uncertainty is thus inherent in this nonlinear recursive design process, which may lead to mental stress on designers. The second postulate then relates a designer's mental stresses to creativity through an inverse U shaped curve (Figure 3.1), which is adopted from the well-known Yerkes-Dodson law (Yerkes & Dodson, 1908). And the mental stress can be qualitatively represented as Equation 1 shows.

$$\begin{aligned} mental \quad stress &= \frac{percieved \quad workload}{(knowledge + skill) * affect} \\ affect &\in (0,1) \end{aligned} \tag{1}$$

where, the parameters are defined as:

- Knowledge (denoted by K): structure of knowledge;
- Skills (denoted by S): thinking styles, reasoning methods, thinking strategy;
- Affect (denoted by A): emotion, feeling, determined by personality, attitude, belief, motive, and availability of cognitive resources;
- Perceived workload (denoted by W^P): a temporal manifestation of the real workload (W^L) through perception.

and the denominator, $(knowledge + skill) * affect$, represents designer's mental capacity.

This model is used to represent Performance-Stress relation in this thesis, by replacing "creativity" with "performance", see Figure 3.2. It has been recognized by many other researchers (Anderson, 1976; Welford, 1973; Westman & Eden, 1996) as a foundation to study the stress-performance relationship qualitatively.

3.1.1 How is Workload Affected

Workload can be defined as an external load assigned to a person whereas mental capacity is the person's ability to handle the external load (Nguyen & Zeng, 2012). Mental stress is directly

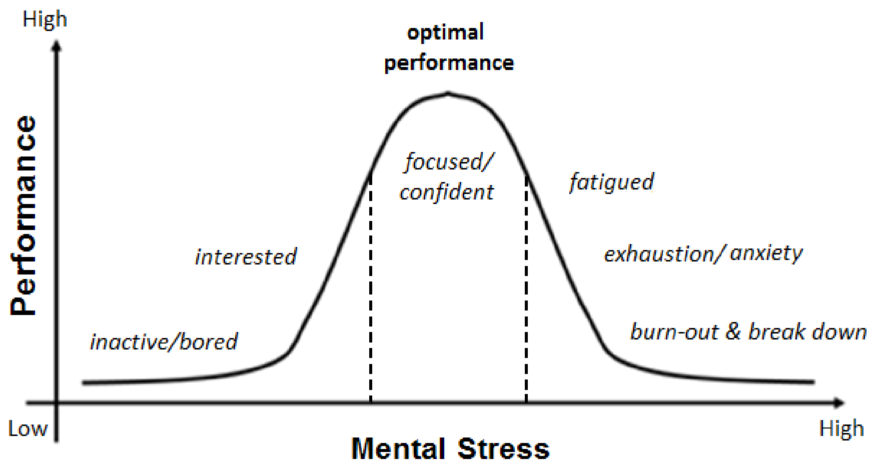

Figure 3.2: The inverse U curve relation between mental stress and performance.

affected by the amount of external workload. A greater workload may trigger a greater mental stress. This workload is associated with the complexity of the problem.

In the performance-stress model, perceived workload (W^P) is a temporal manifestation of the real workload (W^L) through perception. The manifestation of a perceived heavy workload is a feeling in the form of pressure or stress (Kyndt, Dochy, Struyven, & Cascallar, 2011). The real workload alone is not a good measure of perceived workload (Kember & Leung, 1998). There is a gap between the real workload and the perceived workload. Apparently, the closer one's perceived workload to the real workload, indicates a better perception. In addition, perception of workload is not synonymous with time spent, but can be weakly influenced by it (Kember, 2004), and is heavily influenced by content, difficulty, type of assessment (Kember, 2004).

In this research, the perception of workload can be represented by the translation from W^L to W^P illustrated in Figure 3.3. During the perception process, knowledge, skills and affect being used (K^P, S^P and A^P) will together work on W^L and will result in W^P. K^P, S^P and A^P are a portion of related knowledge set, related skill set and affect available at disposal (K^L, S^L and A^L), respectively.

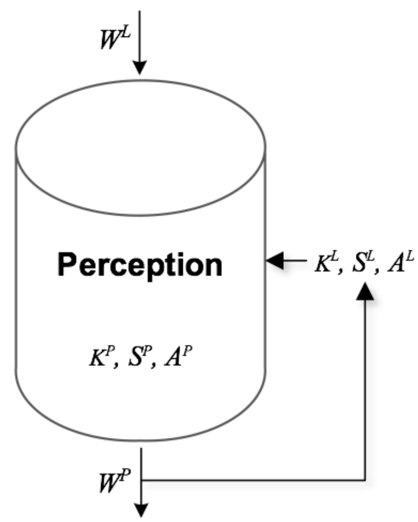

Figure 3.3: The role of perception for workload.

3.1.2 How is Affect Affected

Affect refers to emotion, and any mental state associated with feeling such as tiredness (Salovey, 1997). Research shows that both types of fatigue, physical and emotional fatigue, have negative effects on performance (Barnes & Van Dyne, 2009; Cropanzano, Rupp, & Byrne, 2003; Pilcher & Huffcutt, 1996; Wright & Cropanzano, 1998). Affect is also determined by personality, attitude, belief, motive and stress (Nguyen & Zeng, 2012). Affect will determine how much of a designer's knowledge and skills can be effectively used to solve a problem. The perceived affect is affected by the perceived workload (W^P), perceived knowledge (K^P) and affect (A^L) as shown in Figure 3.4.

3.1.3 How is Knowledge Affected

Knowledge is an abstraction of information built on data, and knowledge leads to understanding, according to the data-information-knowledgeable model shown in Figure 3.5. Knowledge is influenced by the structure of knowledge and the availability of cognitive resources (Nguyen & Zeng, 2012). Perceived workload directly affects the perceived knowledge which is retrieved from long term memory and to be held in working memory for use. The perception on knowledge is shown in Figure 3.6.

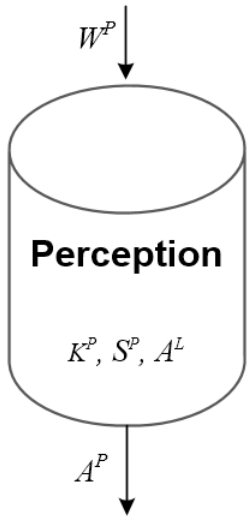

Figure 3.4: The role of perception for affect.

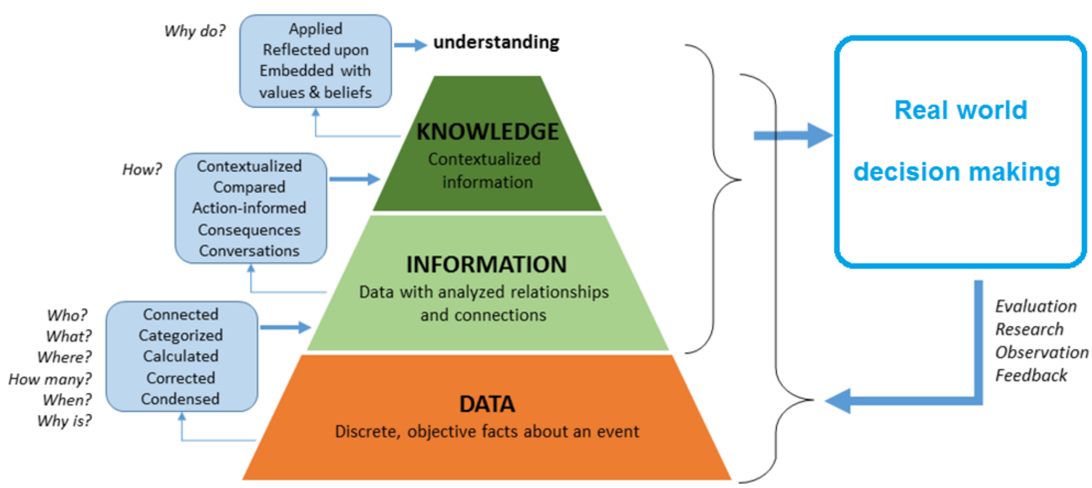

Figure 3.5: Knowledge is an abstraction of information. Modified from (Dennis Bours, 2015).

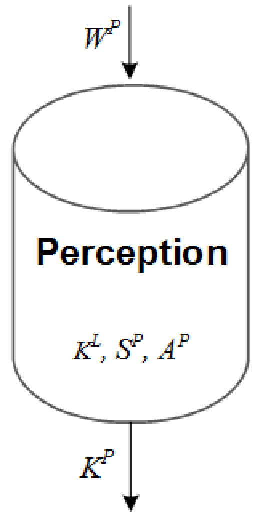

Figure 3.6: The role of perception for knowledge.

Through lessoning, observation, and experience, we collect information about some characteristics and benefits associated with the products and services. Most often in a design process, many important pieces of information are missing, and we must go beyond what we know to fill in the gaps. This process of filling in the gaps is called "inference" (Cartwright, 2015). Our inferences are formed by linking information using cues, heuristics, logic, and other means, and formulating conclusions (Kenyon & Sen, 2015). There are two basic inference processes, induction and deduction, which are high level of perception.

In the EBD methodology, knowledge are represented around the so called product-environment system (PES). The idea behind is that everything except the product itself is the environment. Anything can thus be represented by the PES, shown in Figure 3.7. The product is denoted by S, and its environment is denoted by E, the action from the product to its environment is denoted by $\bar{A}$, and the response from the environment to the product is denoted by $\bar{R}$. It is noteworthy that the product S is a relative term. For example, when designing a car, the car, as a whole part, can be considered a product. Its environment includes, but not limited to, the road, driver, passengers, traffic lights, natural environment, etc. When talking about the engine for the car, the car becomes the environment to the engine.

There are two types of knowledge are required for design: evaluation knowledge and synthesis

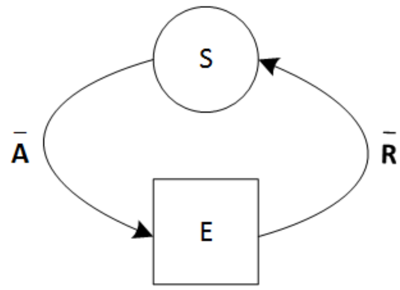

Figure 3.7: The product-environment system.

knowledge. And they can be well represented with the product-environment system.

Evaluation knowledge It represents relation from requirement to solution as

$$\forall E, \forall S: \quad \exists \bar{A} \subset (E \times S) \quad \bar{R} \subset (S \times E), \quad \exists K^e \subset (\bar{A} \times \bar{R})$$

Therefore, evaluation knowledge is a collection of each piece of evaluation knowledge, mapping from actions and responses, between product and its environment, represented as

$$\mathbb{K}^e: \quad \bar{A} \rightarrow \bar{R}$$

Synthesis knowledge It represents relation from solution to requirement as

$$\forall E, \forall S: \quad \exists \mathbb{K}^s = \bigcup_{i=1}^{n} K_i^e \quad K^e \subset (\bar{A} \times \bar{R})$$

Therefore, synthesis knowledge is the collection of all evaluation knowledge to represent the product S, represented as

$$\mathbb{K}^s: \quad S \rightarrow \bigcup_{i=1}^{n} K_i^e$$

These two types of knowledge are in accordance with two skills sit on upper levels of the aforementioned revised Bloom's Taxonomy.

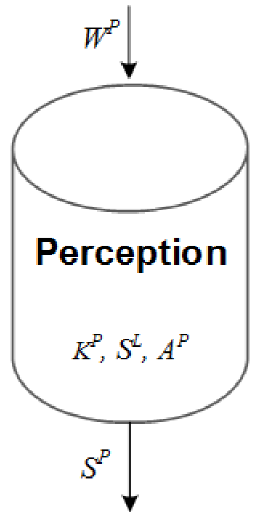

Figure 3.8: The role of perception for skill.

3.1.4 How is Skill Affected

Skills refer to the thinking styles, thinking strategy or reasoning methods (Nguyen & Zeng, 2012). Those are high level of cognitive skills. More concrete skills are considered an implementation or extension of the skill defined in the revised Blooms Taxonomy. For example, several basic skills in an engineering design process were outlined in (Nguyen & Zeng, 2012): identifying problem, searching for information, generate a solution, evaluating alternatives, analyze skill, and synthesis skills. Perceived skill refers to the skill chosen to solve a problem under certain contexts. It is determined by perceived workload (W^P), affect (A^P), perceived knowledge (K^P), and possessed skills (S^L), as Figure 3.8 shows.

It is reported that all humans have the same cognitive or problem-solving structure (Ullman, 2009), then what makes designers so different from each other in terms of the delivered product, no matter concept or final product, being creative or not? Skill plays the critical role. The tremendous success of applying perceptual skills in the revised Bloom's Taxonomy to education presented us a good example. Skill boosts other factors, for instance, knowledge searching skill could help us to expend our knowledge space effectively.

3.1.5 Role of Perception in Engineering Design

Based on the analysis and the recursive logic of design from the EBD, a theoretical perception model for design process can thus be derived as Equation 2 shows.

$$
\begin{aligned}
D_{i+1} &= f^{P}(D_i) \\
D_i &= \left[W_i^P, K_i^P, S_i^P, A_i^P\right] \\
D_0 &= \left[W_0^P, K_0^P, S_0^P, A_0^P\right] = \left[W^L, K^L, S^L, 1\right]
\end{aligned}
\tag{2}
$$

where, D_i represents a design at ith phase. $f^P()$ represents the perception function. As can be seen, each new design phase is the results of a perception of the previous design phase. For each design phase i, the design D_i is a combination of perceived workload W_i^P, related (perceived) knowledge set, related (perceived) skill set (K_i^P), and perceived affect (A_i^P). For the initial condition, we have all our learned knowledge, possessed skill, real workload and full affect at disposal. Apparently this model applies to engineering design.

3.2 Quantification of Designer's Perception

A quantification of one's perception for a design problem indicates a recognition of the real workload. According to ROM (Zeng, 2008), perception can be quantified by three factors: objects (environment components), relations between them, and the priority of asking questions about them. It can be represented by a triangle quantification model shown in Figure 3.9.

When applying this model, a problem raises: the more objects or environment components found, the significantly more interrelations among them. In other words, the relation number exponentially increases with the increasing number of environment components. This can be represented by a matrix as Figure 3.10 shows. For n components, there are $n * n$ relations. In reality, not every a_j^i exists. Based on the quantification model purely, it hinders the evaluation results for complex design problems, due to too many environment components involved in. A dilemma between the theoretical model and the real world application is now faced.

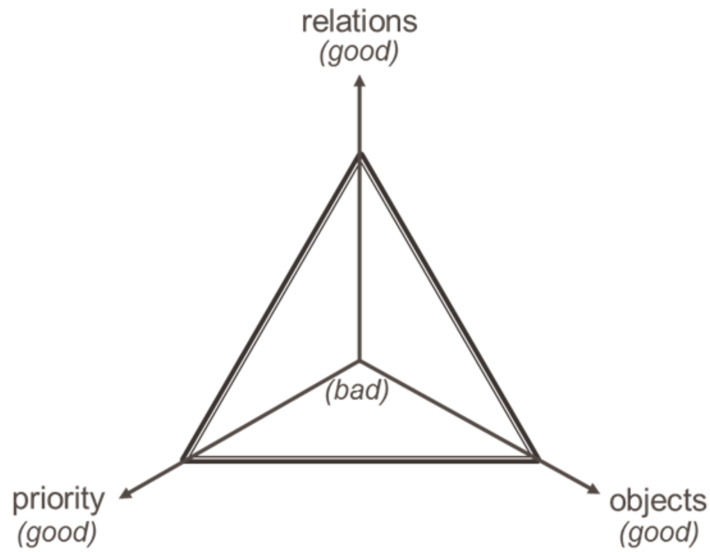

Figure 3.9: The triangle quantification model.

$$\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}$$

Figure 3.10: Matrix representation the interrelations of n components.

What does it really mean for each of the objects and relations? They actually represent the knowledge that one may use to solve a problem. While, since the EBD is a question-driven process, (sub-)problems are represented by questions. Therefore, a more practical quantification process is proposed as following:

- Step 1. Find out all the questions in the order that they should be answered;
- Step 2. Check the order that the subject answered in the experiment;
- Step 3. Score the subject's solution according to the degree of matching in both the order and likelihood to answer the questions.

The theoretical triangle quantification model can be represented by two factors: the "**score** (likelihood to answer a question)" and "**priority** (the order been answered)". Between the two factors, priority is considered more important for perception. It weights more in calculating a final perception rate. In this research, "priority" weights 2/3 of the total, whereas "score" weights 1/3. For each design phase, only the top-most seven questions are evaluated for simplification in this research[1]. The priority wight for each of the seven questions is assigned as Equation 3 shows:

$$\begin{aligned} O_1 &= 2/10 \\ O_2 &= 2/10 \\ O_3 &= 2/10 \\ O_4 &= 1/10 \\ O_5 &= 1/10 \\ O_6 &= 1/10 \\ O_7 &= 1/10 \end{aligned} \tag{3}$$

For the score to each question, denoted by q, a 3-scale value is applied: 1 for answered, 0.5 for partially answered, and 0 for not answered. Therefore, for the i^{th} phase, the final perception rate

[1] This is due to the fact that, for the question asking templates defined in the EBD (M. Wang & Zeng, 2009; Zeng, 2015), seven questions can be asked for a general/primitive design problem statement – "Design a product to do something."

equation can be formed as Equation 4 shows:

$$RC^i = 2/3 * \sum_{j=1}^{n} O_j^i + 1/3 * \sum_{j=1}^{n} q_j^i / n \tag{4}$$

where, j is the question order of the question being evaluating; O_j^i is the priory weight for the j^{th} question (defined Equation 3) in the i^{th} design phase; q_j^i represents the score for the j^{th} question in the i^{th} design phase; and n represents the total question amount to be evaluated. In this case, n = 7.

3.3 Quantification of Designer's Performance

As previously stated, a solution is the best manifestation of a designer's performance in each stage. Therefore, designer's performance is quantified based on how well the solution satisfies the design requirements. The quantification procedure can be represented as following:

- Step 1. Draw the ROM diagram based on the most updated problem statement/descriptions;
- Step 2. Extract the complete requirements (refer to (M. Wang & Zeng, 2009; Zeng, 2015) on how to generate a complete requirement list);
- Step 3. Score the subject's solution to the requirements.

To evaluate if a requirement is satisfied or not, the same 3-scale value system is used: 1 for satisfied, 0.5 for likely to satisfy, and 0 for not satisfied, denoted by t. For the i^{th} phase, the performance rate can be calculated by the following Equation 5:

$$RP^i = \sum_{j=1}^{m} t_j^i / m \tag{5}$$

where, t_j^i represents the satisfactory score for the j^{th} requirement in the i^{th} design phase; and m denotes the number of requirements to be satisfied.

Chapter 4

The Experiment

The objective of this experiment is to test the theoretical model and quantification methods, and to investigate how a designer's perception is related to his/her performance at conceptual design phase.

4.1 Experimental Setup

10 subjects volunteered to participate in the experiment. All of them were graduate students from the Quality System Engineering program at Concordia University without previous industrial experience. Subject 6 to 10 took the INSE6411 Product Design and Methodology course, while subject 1 to 5 did not. They were hence classified into two groups: "course taken" and "non-course taken".

After signing a consent form, every subject was asked to complete an open-ended design task. The setup of the experimental environment is shown in the Figure 4.1. Cameras were used to observe a designer's behavior, to make sure that the subject was focusing on designing. This implies that the "affect" of the subjects stayed at 1 during the design process. The tablet screen was being recorded during the whole design process.

4.2 Experimental Procedures

The following lists the experiment procedures:

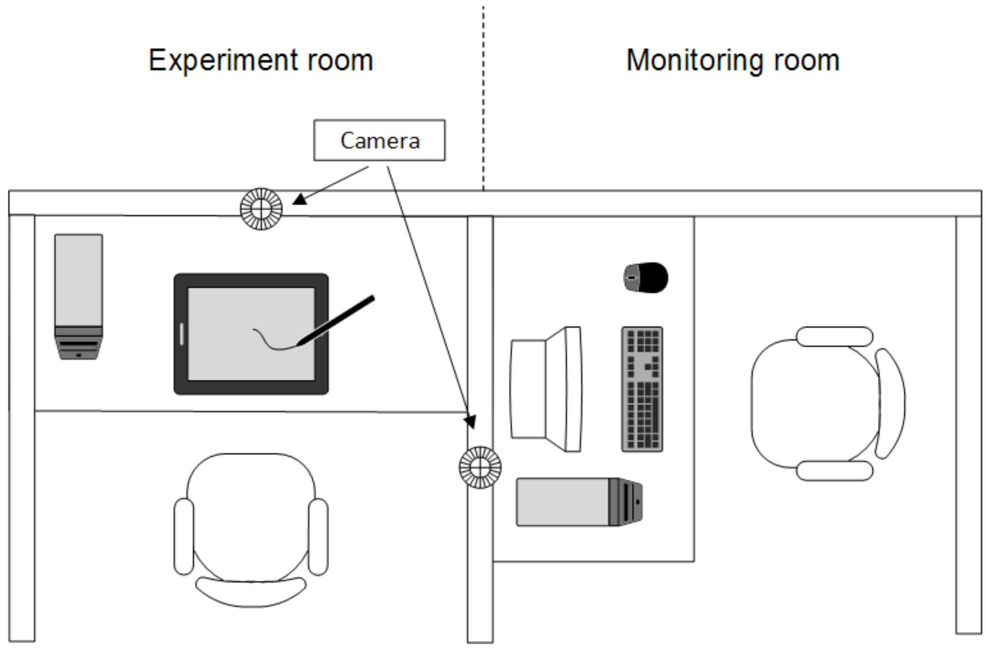

Figure 4.1: The configuration of the experimental environment.

- Step 1: Preparation

  A subject was informed of the experimental procedure. After the subject signed the consent form, he/she was allowed to play with the tablet screen and stylus.

- Step 2: Data collection

  After the subject felt comfortable in using the tablet and stylus for writing and sketching, the experiment started. First, the subject was asked to rest for three minutes with eyes closed. Then, the subject was given the design problem to start. After completed the design task, the subject was asked to rest for another three minutes with eyes closed. Figure 4.2 shows the design task.

- Step 3: Data processing

  For perception evaluation, video data were segmented according to several activities that a subject might perform. Those parameters are chosen based on two criteria: (1) they are easy to be differentiated; (2) they reflect a designer's skill in cognitive domain, perception related in other words. Four major activities has been adopted: sketching, refining, describing, and reflecting. They are the basic activities generalized and summarized from the design process,

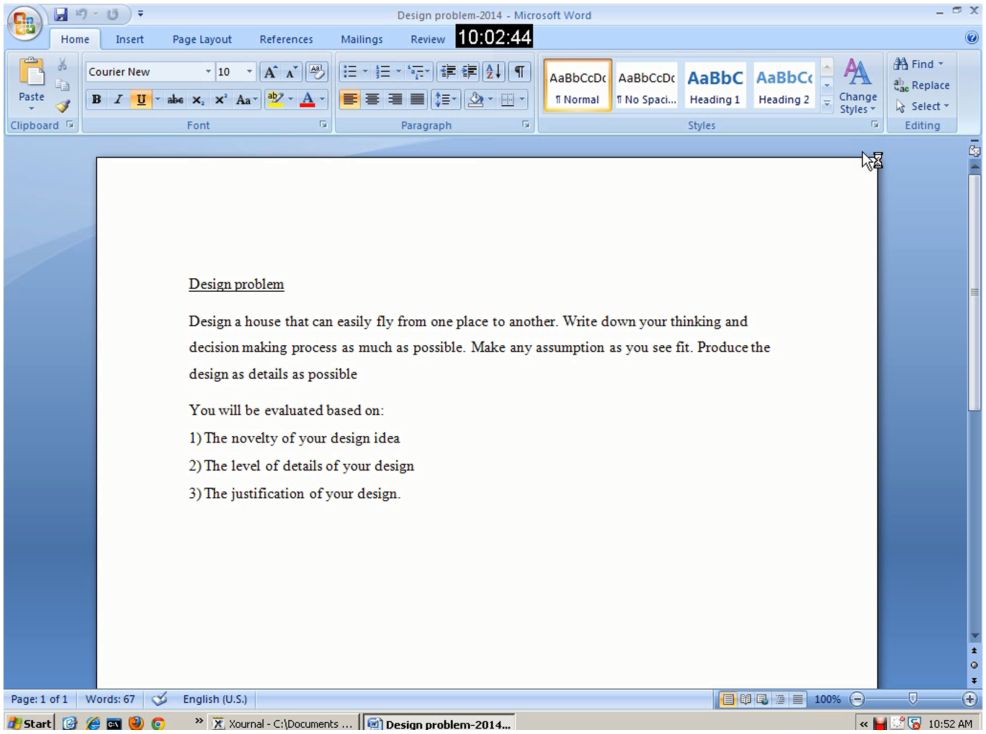

Figure 4.2: The design problem with requirements.

based on the revised Bloom's Taxonomy (refer to Figure 4.3).

- Sketching: The subject is drawing a solution.
- Describing: The subject is clarifying his design by writing.
- Refining: The subject is modifying his sketching or writings.
- Reflecting: The subject stops writing or sketching for more than 3 seconds, and is reviewing his design or the design task.

Though the activity, reflecting, cannot be referred in the revised Bloom's Taxonomy directly, it implies several activities across different levels such as level of "understand", "apply" and "evaluate". Based on a video clip merely, it is impossible to tell which activity was being involved, since multiple activities might just happen in a row in the subject's brain, when he/she stopped writing or sketching. Therefore, reflecting is used as a superset to serve the aforementioned criterion 1.

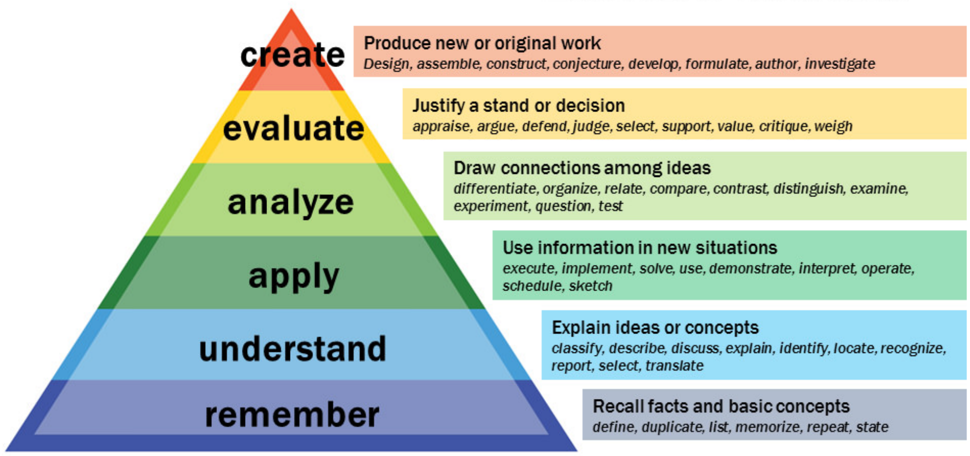

Figure 4.3: The revised Bloom's Taxonomy was used as a reference to identify design activities from cognitive perspective. Adopted from (Armstrong, 2016)

Requirements were then extracted from the design solution and were compared with that of a benchmark. The benchmark was made by an EBD expert by starting with the same design task. It evolved based on the inputs from a subject. For each design phase, the ROM was expanded and EBD method was applied to generate more environment components, and the complete requirements.

- Step 4: Data analysis

  The perception rates and performance rates were calculated respectively. All the statistical results were generated with the IBM SPSS Statistics 22 software.

4.3 Data Processing

Subject 3 is taken as an example to illustrate the data processing and data analysis process. A thumbnail of the design process of the subject 3 is given in the Figure 4.4. According to the video segmentation rules, it was segmented as Figure 4.5 shows. The segmentation outlines a time course of some basic skills being used in a design process, and it is the reflection of the subject's perception.

Theoretically, each activity may represent the beginning of a new design phase. In this thesis, for simplicity, a new phase is considered beginning when either one of the following happened and

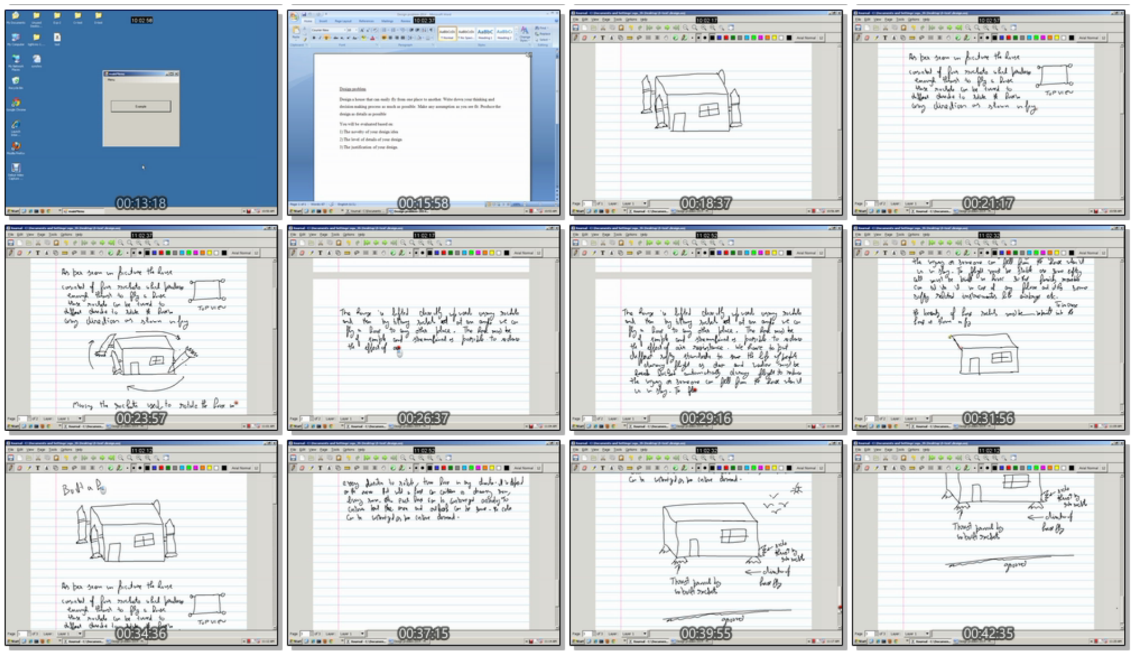

Figure 4.4: A thumbnail of the design process of the subject 3.

1	Activity Marker	Timestamp	Durition (s)	Remarks
2	Reflecting	0:14:50	79	Start reading statement
3	Sketching	0:16:09	199	Sketching p1: house with 4 rockets (side and top views)
4	Describing	0:19:28	114	
5	Sketching	0:21:22	72	Draw p2: rocket can rotate to turn the hosue
6	Refining	0:22:34	63	draw turning system on P2
7	Describing	0:23:37	39	
8	Reflecting	0:24:16	22	Check the statement again
9	Describing	0:24:38	10	
10	Reflecting	0:24:48	134	
11	Describing	0:27:02	120	
12	Reflecting	0:29:02	7	
13	Describing	0:29:09	95	
14	Reflecting	0:30:44	21	
15	Describing	0:31:05	32	
16	Sketching	0:31:37	72	Sketching p3: vetical thrust to leave ground
17	Describing	0:32:49	100	
18	Describing	0:34:29	35	Go back to top to add title
19	Describing	0:35:04	95	Go back continue writing
20	Reflecting	0:36:39	87	Check statement again
21	Refining	0:38:06	108	Refining p3 as a new picutre p4: side thrust, flying objects, sun, direction
22	Refining	0:39:54	46	Refining p1: clarify objects in the design
23	Reflecting	0:40:40	14	Go thtough Sketching and writings
24	Refining	0:40:54	23	Refining on p3:clarify pbjects
25	Reflecting	0:41:17	32	
26	***Done***	0:41:49	1619	
27				

Figure 4.5: Video segmentation for subject 3.

new objects and/or relations were provided/removed at the end of the phase.

- A subject started sketching;
- A subject started refining;
- A subject finished reflecting.

Thus, there were 11 design phases identified, which started at 0:16:09, 0:21:22, 0:22:34, 0:24:38, 0:27:02, 0:29:09, 0:31:05, 0:31:37, 0:38:06, 0:39:54, 0:40:54, respectively. Each solution at the end of each phase was evaluated. The first solution at 0:21:22 was taken to be compared to the benchmark (refer to Appendix B for details), resulted the first perception rate (RC^1) sitting at 0.1571 and first performance rate (RP^1) sitting at 0.46.

4.4 Data Analysis

4.4.1 Statistics of Perception

	Subject_1	Subject_2	Subject_3	Subject_4	Subject_5	Subject_6	Subject_7	Subject_8	Subject_9	Subject_10
1	.1810	.0905	.1571	.1810	.1571	.4048	.5619	.6095	.4524	.3143
2	.3381	.2714	.3381	.4286	.3381	.5190	.5190	.7000	.5857	.5857
3	.4524	.3381	.3143	.	.4048	.4952	.5857	.7429	.5857	.5429
4	.4286	.4286	.3381	.	.5857	.5190	.6762	.7667	.6095	.5190
5	.5190	.	.4524	.	.5190	.7000	.6524	.7429	.7429	.5190
6	.	.	.4524	.	.	.6762	.7238	.7905	.7238	.7476
7	.	.	.4952	.	.	.5857	.7429	.8333	.7667	.7000
8	.	.	.5190	.	.	.6762	.8333	.7905	.7429	.7000
9	.	.	.5857	.	.	.7476	.8810	.7667	.7667	.7000
10	.	.	.6762	.	.	.7238	.	.8810	.7667	.7905
11	.	.	.5857	.	.	.7714	.	.8571	.8810	.7476
12	.	.	.	.	.	.	.	.9524	.8571	.7238
13	.	.	.	.	.	.	.	.9524	.	.7905
14	.	.	.	.	.	.	.	.	.	.7238
15	.	.	.	.	.	.	.	.	.	.8333
16	.	.	.	.	.	.	.	.	.	.8810
17	.	.	.	.	.	.	.	.	.	.9048
18	.	.	.	.	.	.	.	.	.	.9286

Figure 4.6: Perception rates for all subjects respecting to their design phases.

Perception rates for all subjects respecting to their design phases are presented in Figure 4.6. Apparently, the number of design phases varies significantly among subjects: ranging from 2 phases (subject 4) to 18 phases (subject 10) for this experiment. According to the descriptive statistics for

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Subject_1	5	.1810	.5190	.383820	.1305837
Subject_2	4	.0905	.4286	.282150	.1430889
Subject_3	11	.1571	.6762	.446745	.1496471
Subject_4	2	.1810	.4286	.304800	.1750796
Subject_5	5	.1571	.5857	.400940	.1669552
Subject_6	11	.4048	.7714	.619900	.1208964
Subject_7	9	.5190	.8810	.686244	.1219442
Subject_8	13	.6095	.9524	.798915	.0968572
Subject_9	12	.4524	.8810	.706758	.1243573
Subject_10	18	.3143	.9286	.702911	.1569291
Valid N (listwise)	2				

Figure 4.7: Descriptive statistics for each subject respecting to their design phases.

each subject shown in Figure 4.7, it is observed that the means seem falling into two groups, as expected. In order to do a between-group comparison, within-group statistical validation is needed. Therefor, the first sub-hypothesis can be stated as:

H_0^1: *Subject 1 to 5 belong to the same group in terms of perception.*

From the T-Test results shown in Figure 4.8, it is noticed that the significance value for subject 4 sits at 0.246, where the confidence level is 95%. As $0.246 > (1 - 95\%)$, the hypothesis (H^1) is rejected. Subject 4 does not belong to this group. Therefore, subject 4 cannot be used for between-group comparison for perception analysis. For the non-course taken group, a similar hypothesis could not be rejected, according to its T-Test results shown in Figure 4.9.

The between-group result is shown in Figure 4.10, subject 4 is not included in this comparison. It is obvious that, the course-taken group outperformed the non-course taken group by a significant margin. The indicates that, learning a design methodology can significantly improve a designer's perception.

4.4.2 Statistics of Performance

For performance, the rates for all subjects, respecting to their design phases, are presented in Figure 4.11, and the descriptive statistics are shown in Figure 4.12. From the descriptive statistics,

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Subject_1	5	.383820	.1305837	.0583988
Subject_2	4	.282150	.1430889	.0715444
Subject_3	11	.446745	.1496471	.0451203
Subject_4	2	.304800	.1750796	.1238000
Subject_5	5	.400940	.1669552	.0746646

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Subject_1	6.572	4	.003	.3838200	.221679	.545961
Subject_2	3.944	3	.029	.2821500	.054464	.509836
Subject_3	9.901	10	.000	.4467455	.346211	.547280
Subject_4	2.462	1	.246	.3048000	-1.268228	1.877828
Subject_5	5.370	4	.006	.4009400	.193638	.608242

Figure 4.8: T-Test statistics for the non-course taken group in terms of their perception rates.

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Subject_6	11	.619900	.1208964	.0364516
Subject_7	9	.686244	.1219442	.0406481
Subject_8	13	.798915	.0968572	.0268634
Subject_9	12	.706758	.1243573	.0358989
Subject_10	18	.702911	.1569291	.0369885

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Subject_6	17.006	10	.000	.6199000	.538681	.701119
Subject_7	16.883	8	.000	.6862444	.592510	.779979
Subject_8	29.740	12	.000	.7989154	.740385	.857446
Subject_9	19.687	11	.000	.7067583	.627745	.785771
Subject_10	19.003	17	.000	.7029111	.624872	.780950

Figure 4.9: T-Test statistics for the course-taken group in terms of their perception rates.

Perception_MEAN

Group	Mean	N	Std. Deviation
course_taken	.702946	5	.0640316
non-course_taken	.378414	4	.0694563
Total	.558709	9	.1819750

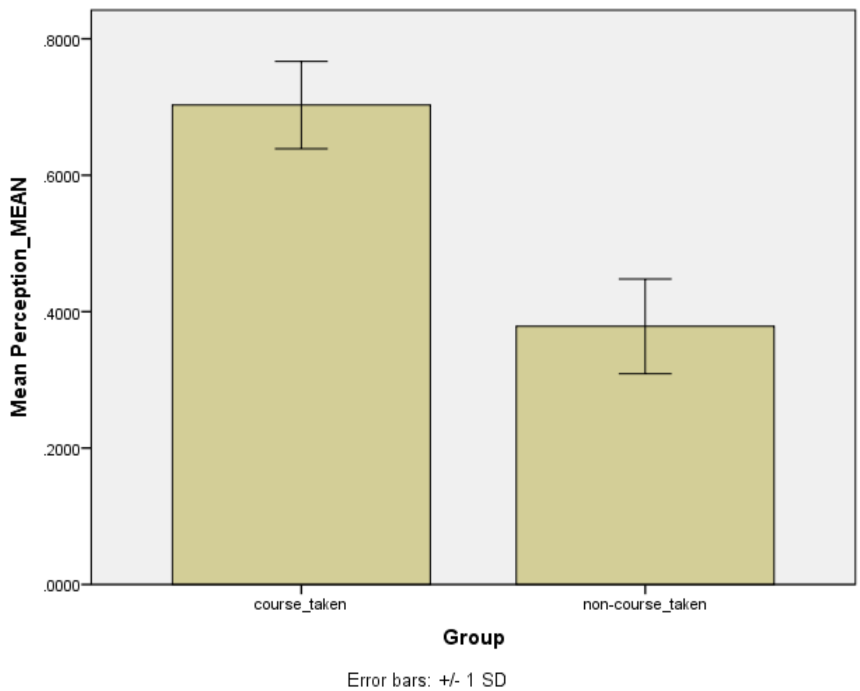

Figure 4.10: Perception rate comparison between two groups.

	Subject_1	Subject_2	Subject_3	Subject_4	Subject_5	Subject_6	Subject_7	Subject_8	Subject_9	Subject_10
1	.38	.32	.46	.22	.37	.12	.13	.29	.00	.17
2	.42	.37	.46	.22	.38	.24	.22	.33	.07	.24
3	.42	.42	.57	.	.45	.28	.33	.46	.26	.46
4	.43	.44	.58	.	.53	.36	.47	.47	.33	.50
5	.43	.	.59	.	.54	.42	.54	.54	.56	.55
6	.	.	.59	.	.	.58	.67	.54	.64	.58
7	.	.	.61	.	.	.59	.67	.59	.68	.58
8	.	.	.62	.	.	.66	.73	.62	.69	.58
9	.	.	.67	.	.	.69	.73	.67	.71	.59
10	.	.	.67	.	.	.76	.	.77	.77	.59
11	.	.	.67	.	.	.76	.	.79	.79	.64
12	.	.	.	.	.	.	.	.82	.79	.64
13	.	.	.	.	.	.	.	.83	.	.69
14	.	.	.	.	.	.	.	.	.	.72
15	.	.	.	.	.	.	.	.	.	.74
16	.	.	.	.	.	.	.	.	.	.75
17	.	.	.	.	.	.	.	.	.	.75
18	.	.	.	.	.	.	.	.	.	.77
19										

Figure 4.11: Performance rates for all subject respecting to their design phases.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Subject_1	5	.38	.43	.4160	.02074
Subject_2	4	.32	.44	.3875	.05377
Subject_3	11	.46	.67	.5900	.07403
Subject_4	2	.22	.22	.2200	.00000
Subject_5	5	.37	.54	.4540	.08019
Subject_6	11	.12	.76	.4964	.22308
Subject_7	9	.13	.73	.4989	.22646
Subject_8	13	.29	.83	.5938	.17886
Subject_9	12	.00	.79	.5242	.28465
Subject_10	18	.17	.77	.5856	.16511
Valid N (listwise)	2				

Figure 4.12: Descriptive statistics for each subject in terms of their performance rates.

intuitively, two groups are expected based on the means. Similar to the perception test, in order to do a between-group comparison, within-group validation should be done first. The second hypothesis is made as:

H_0^2: *Subject 1 to 5 belong to the same group in terms of performance.*

From the T-Test results shown in Figure 4.13, it is noticed that the subject 4 is removed from the tests since its standard divination is 0. However, we could not reject the hypothesis that subjects 1-5 belong to the same group. The grouping for subjects 6-10 is validated by Figure 4.14.

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Subject_1	5	.4160	.02074	.00927
Subject_2	4	.3875	.05377	.02689
Subject_3	11	.5900	.07403	.02232
Subject_4	2	.2200	.00000[a]	.00000
Subject_5	5	.4540	.08019	.03586

a. t cannot be computed because the standard deviation is 0.

One-Sample Test

	Test Value = 0					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
Subject_1	44.858	4	.000	.41600	.3903	.4417
Subject_2	14.412	3	.001	.38750	.3019	.4731
Subject_3	26.434	10	.000	.59000	.5403	.6397
Subject_5	12.660	4	.000	.45400	.3544	.5536

Figure 4.13: T-Test statistics for the non-course taken group in terms of their performance rates. T-Test on Subject 4 cannot be proceeded.

The between-group result is shown in Figure 4.15. We could not find out a significant difference as the error bar for the non-course taken group is so high.

4.4.3 Statistics of Correlation

The mean of perception of all phases for each subject is chosen as the perception indicator. Whereas, the mean of performance is chosen as the performance indicator. For the correlation

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Subject_6	11	.4964	.22308	.06726
Subject_7	9	.4989	.22646	.07549
Subject_8	13	.5938	.17886	.04961
Subject_9	12	.5242	.28465	.08217
Subject_10	18	.5856	.16511	.03892

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Subject_6	7.380	10	.000	.49636	.3465	.6462
Subject_7	6.609	8	.000	.49889	.3248	.6730
Subject_8	11.971	12	.000	.59385	.4858	.7019
Subject_9	6.379	11	.000	.52417	.3433	.7050
Subject_10	15.046	17	.000	.58556	.5034	.6677

Figure 4.14: T-Test statistics for the course taken group in terms of their performance rates.

between perception and performance, a third hypothesis is made:

H_0^3: *A significant positive correlation exits between perception and performance.*

From the results shown in Figure 4.16, we can conclude that a significant positive correlation exists between perception and performance, as the significance value 0.014 is less than 0.05. The means that the main hypothesis of this research, “A designer who has a good perception of a design problem tends to deliver a good performance.”, is therefore validated.

4.4.4 Traditional Evaluation Method

One might argue that, some of the subjects from the course-taken group used EBD as the design methodology to guide their design, it is not very fair to compare the solution to a benchmark which was done by following the same procedure. To ease this concern, a conventional evaluation method, expert rating, was employed to evaluate the value of the skill and knowledge presented in the solution, as a quick comparison. The design solutions has been evaluated by using fundamental engineering reasoning criteria based on critical thinking concepts and tools (Paul, 2006) and the Criteria for Accrediting Engineering Technology Programs (ABET, 2014). Table 4.1 lists the criteria

Performance_MEAN

Group	Mean	N	Std. Deviation
course_taken	.539780	5	.0469398
non-course_taken	.413500	5	.1331512
Total	.476640	10	.1152760

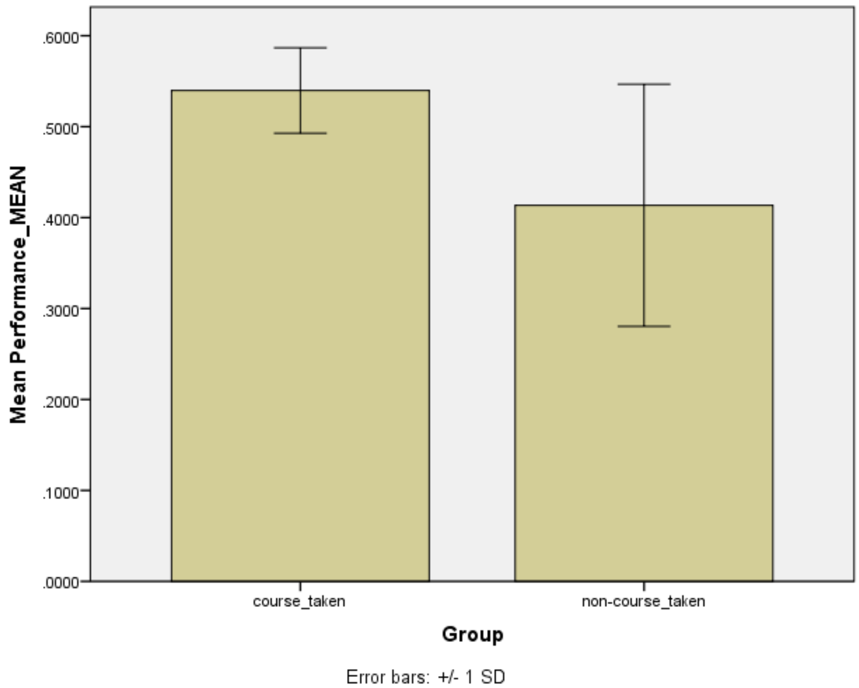

Figure 4.15: Performance rate comparison between two groups.

Correlations

		Perception_MEAN	Performance_MEAN
Perception_MEAN	Pearson Correlation	1	.744*
	Sig. (2-tailed)		.014
	N	10	10
Performance_MEAN	Pearson Correlation	.744*	1
	Sig. (2-tailed)	.014	
	N	10	10

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 4.16: A significant positive correlation found between perception and performance.

for the evaluation. Verdict is given for each criterion in 5 different levels: N/A, Limited, Average, Good, and Outstanding. This set of criteria is typically used in a methodical approach to analyze the structure and completeness of engineering artefacts (documents, designs, tools, etc.). We therefore compared the results documented in experiment with the ideal solution template/pattern designed by an experienced designer.

Table 4.1: The evaluation criteria.

#	Description
1	Establishing purpose
2	Understanding the problem
3	Identification of assumptions
4	Specification of viewpoint
5	Data, information and evidence
6	Concepts and theories
7	Inferences
8	Implications and consequence

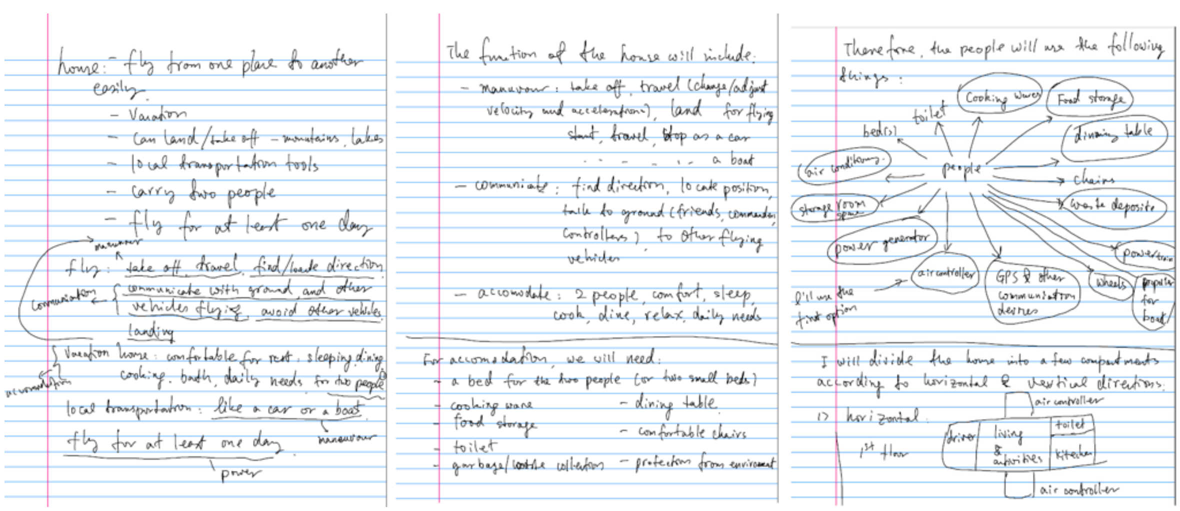

Figure 4.17: The design solution from subject 8.

As an illustration, the design solution of subject 3 and the corresponding evaluation table are shown in Figure 4.5 and Table 4.2, respectively. Figure 4.17 and Table 4.3 show the results from subject 8, as a comparison.

The performance scores given by experts for all subjects are graphically represented as in Figure

Table 4.2: Evaluation of the design solution from subject 3.

Criteria	Verdict	Commands	Example
Establishing purpose	N/A	It has been given in the design problem statement.	N/A
Understanding the problem	Average	The designer limited the house to a house-shaped object.	House with rockets
Identification of assumptions	Limited	Most assumptions were not well justified in the design solution and their criticality was missing.	4 rockets in the first drawing, thrust by side rocket in the last drawing
Specification of viewpoint	Good	Considered both taking off and turning in to different directions.	Different rocket should be used; side thrust by side rocket
Data, information and evidence	Limited	One of the great challenge to an open-ended engineering design is the overload of information available, despite the inaccessible data for non-professionals.	Engine profiling data, laws and regulation from authorities (e.g., FAR)
Concepts and theories	Average	The concepts and theories behind aircraft design are well established and the body of knowledge is widely known and accessible.	The drawings; Moving the rocket angle to rotate house in any direction.
Inferences	Limited	It is indeed a very complex system to be designed. The interpretation of the design choices is a very difficult analysis process even for experts. Designer jumped into solution directly without proper analyses and adopted existing concepts/solution. It is acceptable, but inferences are very limited.	Engine/rocket positioning and I/O interfaces, partner responsibility, certification bodies.
Implications and consequence	N/A	The design solution does not seem an output of a well-structured/systematic approach that can be well repeated by other designers. It is more of a collection of random thoughts grouped together.	The design process is too subjective, and hard to follow by others

Table 4.3: Evaluation of the design solution from subject 8.

Criteria	Verdict	Commands	Example
Establishing purpose	N/A	It has been given in the design problem statement.	N/A
Understanding the problem	Outstanding	The designer provided a step-by-step approach to define and refine the problem. Most of the critical functional and structural components are accurately identified. The whole process is of a professional.	Flying maneuvers; proper accommodation for human being; communication issues, etc.
Identification of assumptions	Outstanding	The assumptions are well established. And they are reasonable, practical and necessary from engineering's perspective.	2 people, fly for at least one day
Specification of viewpoint	Outstanding	Using modularized sub-solutions to from a final solution. Each module was well analyzed and reasoned.	
Data, information and evidence	Good	One of the great challenge to an open-ended engineering design is the overload of information available, despite the inaccessible data for non-professionals. The solution shows reasonable amount of information and evidence.	Functional decomposition, structural synthesis.
Concepts and theories	Outstanding	The concepts and theories behind this design are well established and the body of knowledge is widely accessible. Unlike many other design process, this one does not jump into existing solution at the beginning, but through an analysis process to find out a tailored solution for each sub-problems.	The modules, the sketch.
Inferences	Average	The assumptions make the design solution more reasonable and logical. For such a complex design problem, lack of domain knowledge is understandable, but an already a good solution at conceptual level.	Engine/rocket positioning and I/O interfaces, partner responsibility, certification bodies.
Implications and consequence	Good	A well-structured decomposing strategy that is clear to understand the design logic, and is easy to follow for problem solving.	The whole process

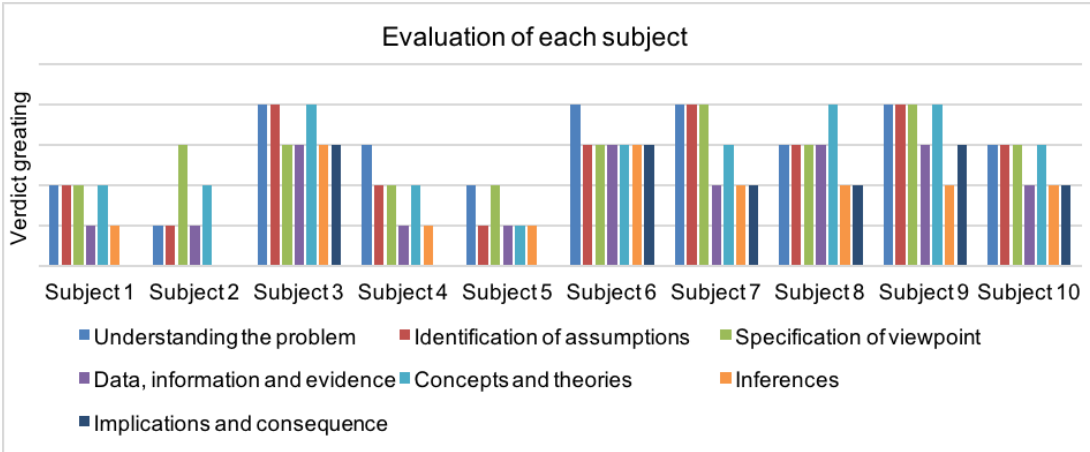

Figure 4.18: Evaluation for each subject (Subjects 1-5 belong to the non-course-taken group, whereas subjects 6-10 belong to the course-taken group).

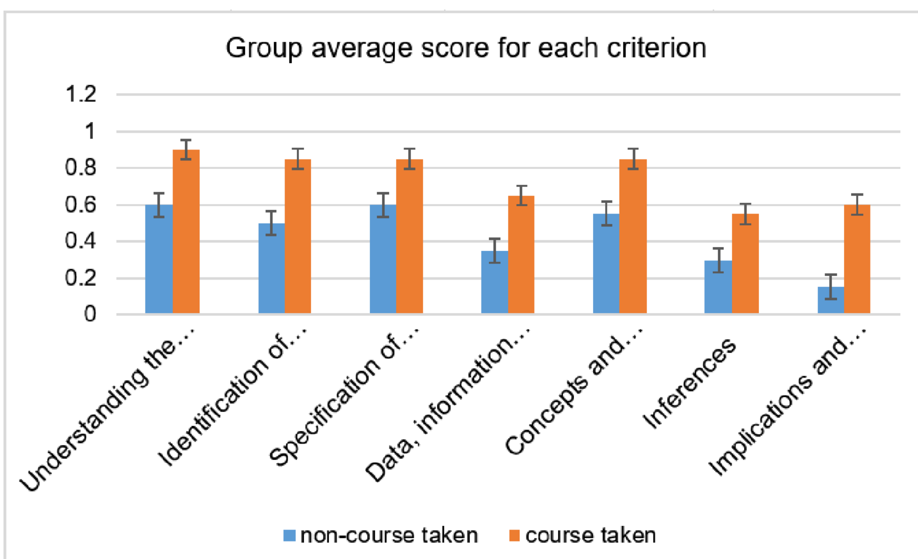

Figure 4.19: Group average score for each criterion.

4.18. From the normalized score comparison between two groups respecting each criterion (shown in 4.19), it is obvious that the course taken group outperformed the non-course taken in each of the criterion. This suggested that a designer who took the Design Methodology course tends to perform better than those who did not.

Correlation between two performance evaluation methods

To evaluate the similarity between two performance evaluation methods, namely, the proposed method and expert rating, a forth hypothesis is made:

> H_0^4: *The proposed performance evaluation delivers similar results with that of the expert rating.*

Before testing this hypothesis directly, the evaluation results of two performance methods were plotted in Figure 4.20. Apparently, there was a major different for subject 5's final performance: The proposed method rated a lot higher compared to the expert rating, whereas the others were comparable. This may due to the fact that, the final evaluation criteria from two methods reflect slightly different perspectives, and the subject 5 highlights the difference more rather than similarities. Nevertheless, according to the correlation test result shown in Figure 4.21, it is concluded that a significant positive correlation exists between two methods ($0.006 < 0.01$). Therefore, the hypothesis 4 cannot be rejected, and is validated.

4.5 How to Improve Designer's Performance Through Perception

Since designer's perception is positively correlated to performance in conceptual design, by following the proposed perception evaluation approach (i.e., ask/answer the right question at right time) to improve one's perception, tends to improve one's performance.

4.6 Discussion

Due to concurrent fashion of solution and design problem evolving, the requirements evolves as well from time to time, from persons to persons, from scenarios to scenarios, which makes the

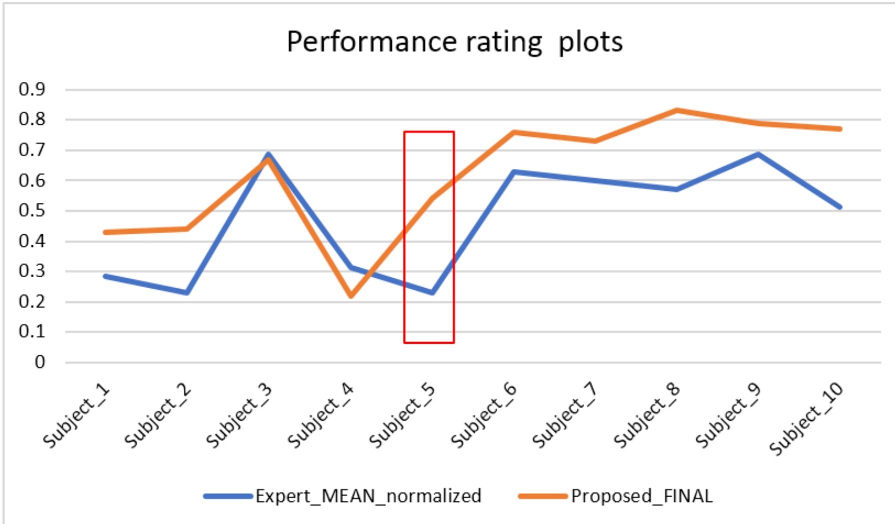

Figure 4.20: Performance rating plots of the two performance evaluation methods.

Correlations

		Expert_MEAN_normalized	Proposed_FINAL
Expert_MEAN_normalized	Pearson Correlation	1	.794**
	Sig. (2-tailed)		.006
	N	10	10
Proposed_FINAL	Pearson Correlation	.794**	1
	Sig. (2-tailed)	.006	
	N	10	10

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 4.21: A significant positive correlation found between two performance evaluation methods.

Report

Expert_MEAN_normalized

Group	Mean	N	Std. Deviation
course_taken	.600000	5	.0638934
non-course_taken	.348576	5	.1920880
Total	.474288	10	.1891372

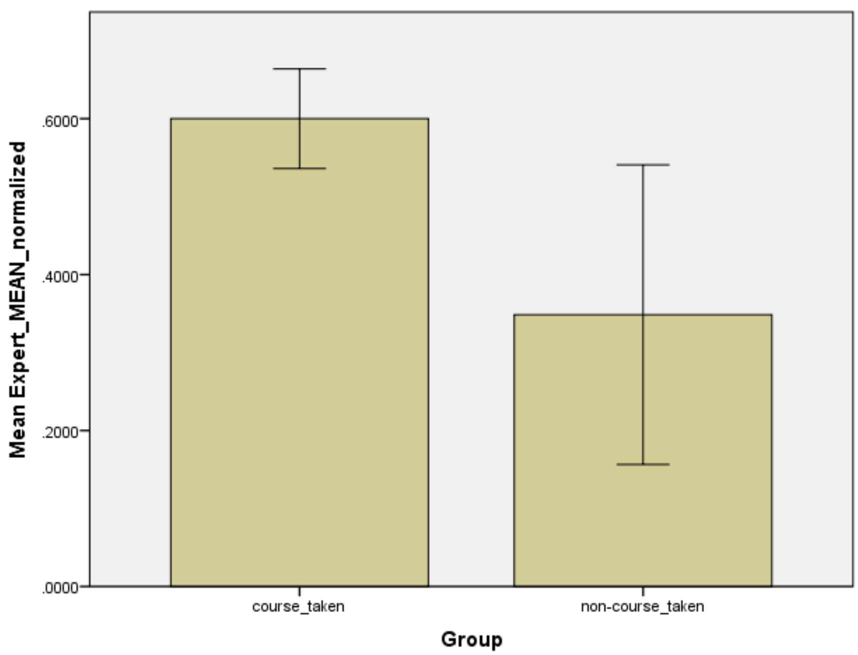

Figure 4.22: Performance rate comparison between two groups from expert rating.

engineering design recursively progress toward to a final solution that satisfy all the requirements.

Back to the experimental results, most of the subjects in the non-course taken group were considered lack of skill(S). They jumped to a solution directly. While, subjects in the course-taken group, considered with better skill (a design methodology), were starting with defining the engineering design problem. The results indicated that a design methodology would significantly increase one's perception.

However, for performance comparison between groups (Figure 4.15), we could visually but could not statistically draw a conclusion that a methodology will help designer's performance. The similar phenomenon can be seen from the between-group result shown in Figure 4.22, for expert rating. To further investigate the cause, the performance rates for each of the subject were plotted in Figure 4.23. As can be seen from this figure, subject 3 and subject 4 performed significantly differently. It seemed that they did not belong to the same group in terms of performance. When doing the test, the huge variance between those two and the similar mean (of those two) with others hindered the within-group test, and made it impossible to reveal the performance difference for between group test. This might due to the fact that the sample size (5, in this research) for within group validation was too small, as 40% of the within-group samples (2 out of 5) were suspicious as outliars. If those two (subject 3 and subject 4) were removed, the performance comparison between two groups (Figure 4.24) shows significant difference. This is also true for expert rating. In this way, we can conclude that learning a design methodology can improve a designer's performance as well.

Moreover, for subject 3, he/her performed very well, as good as the course-take subjects. This indicated that performance can be improved by other means. However, improve one's performance by improving one's perception, as suggested in the previous section, is more "under control", as the perception evaluating method presented in this research follows an objective and systematic manner. Anyone, including oneself, can make used of it as a right guiding tool in conceptual design phases.

Finally, though the proposed model represents the role of perception in all design phases, the proposed perception and performance evaluation methods are more for conceptual design. The reason why this limitation exists is that when domain knowledge involves in detailed design or embodiment design phases, it becomes very difficult to evaluate the feasibility/likelihood to answer

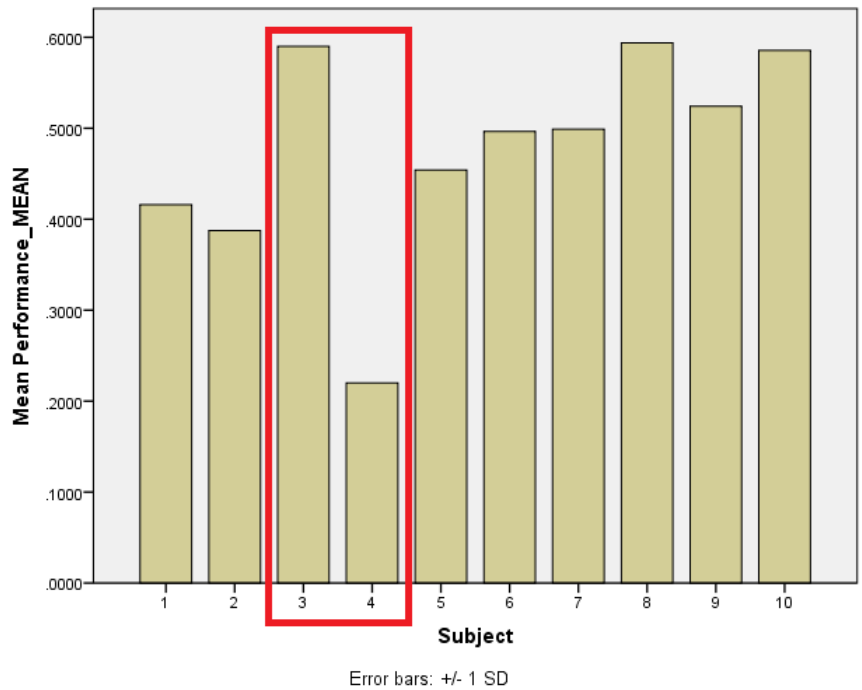

Figure 4.23: Performance plot for all subjects evaluated from the proposed method.

a question or satisfy a requirement, due to our knowledge and skill limitations. Expert rating might have advantages over the proposed method in such a circumstance.

I hope this research is one step in the right direction to study designer's perception and its correlation with designer's performance.

Report

Perception_MEAN

Group	Mean	N	Std. Deviation
course_taken	.702946	5	.0640316
non-course_taken	.355637	3	.0642144
Total	.572705	8	.1892905

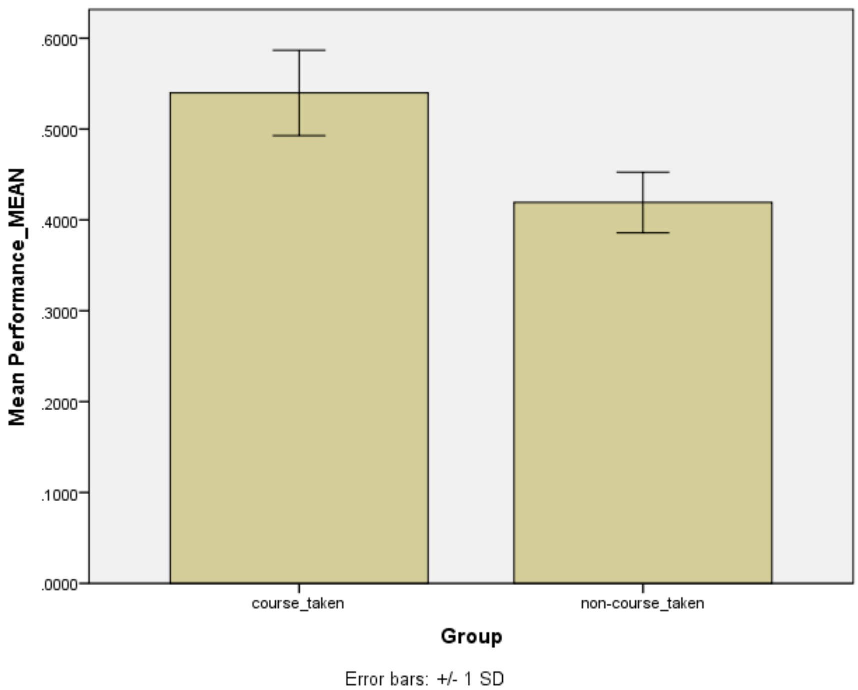

Figure 4.24: Performance rate comparison between two groups without subject 3 and 4 evaluated from the proposed method.

Chapter 5

Case Studies - Engineering Design Applications

The case studies presented in this chapter serve two purposes: (1) As successful applications on which I reflected and eventually inspired my research in studying the roles of perception in engineering design. (2) As illustrations of the effectiveness of the question-driven procedure, in order to maintain correct perception, and led to success in real engineering design applications, regardless of domains.

5.1 Conceptual Design Application - Aerospace Pylon Design[1]

5.1.1 Background

In this fast-paced world, enterprises strive for strategies and ways to promote their productivity, efficiency and competitiveness. With the rapidly changing realm of technologies and exponentially increasing amount of information at our disposal, robust collaboration strategies are vital, especially for enterprises who expand their business worldwide. During collaboration activities, many challenges emerge, e.g., novice training, knowledge transfer, intellectual property (IP) protection, etc. Internal or external training sessions are thus designed for those problems. How to enhance the effectiveness of such activities attracts much attention. There are many books and articles on the study

[1] The content of this section has been published as a conference paper in (Tan, Zeng, Huet, & Fortin, 2013)

of training design, training evaluation, deliverability in multidisciplinary and multilevel (Aguinis & Kraiger, 2009; Albino, Garavelli, & Gorgoglione, 2004; Arthur Jr, Bennett Jr, Edens, & Bell, 2003; Gentner, Loewenstein, & Thompson, 2003; Kirkpatrick & Kirkpatrick, 2008). However, in this case study, we focused on effective learning from a different perspective - reverse engineering, with theory-based principles.

In order to demonstrate how a novice can rapidly and systematically develop design knowledge in a specified domain using a reverse engineering process, a student with a Computer Engineering background conducted a case study on the design of an aerospace pylon, within a short time frame. The topic is already a very challenging problem for experienced aircraft designers, thus seemingly impossible for a novice designer lacking the appropriate background. Experts are able to render a sophisticated design whereas novices tend to provide ill-structured solutions due to their lack of knowledge and experience. Ahmed and Wallace (2004) found that novice designers were hardly aware of their knowledge needs. When facing a problem, novices are overwhelmed by the options available (Gamma, Helm, Johnson, & Vlissides, 1994). Similar results were shown in (Ball, Ormerod, & Morley, 2004; Choy, Lee, Lau, & Choy, 2005; Seitamaa-Hakkarainen & Hakkarainen, 2001). For a novice who wants to get the domain knowledge in a very short time, (s)he has to either be equipped with a very powerful and systematic methodology as guidance to start, or work along with experts to get insights from the design process and design methodology. With the adequate resources, design and reverse engineering are feasible for a person or a small group who wants to start a big project. In this study, Environment-Based Design (EBD) methodology is employed to conduct the design and reverse engineering of the pylon at a conceptual design level. It was chosen because it presents the advantage and the capability of presenting objects and their relationships intuitively (Z. Y. Chen & Zeng, 2006; Tan, Zeng, Chen, Milhim, & Schiffauerova, 2012; Zeng & Chen, 2005), which is helpful for a thorough understanding of the design concepts in a logical and systematic manner.

For this case, one sentence of the design objective extracted from a Statement of Work of a student capstone project in the aerospace engineering department of the École Polytechnique de Montréal was set as the input for the validation of the effectiveness of the EBD theory in the design and reverse engineering of the project brief: the design of an aircraft pylon. No data from the project was accessible for graduate student who conducted this case study. The resources were limited to books available at university and public libraries as well as public resources on the Internet. The evaluation of the final results was given by the experts supervising this project.

5.1.2 Aircraft Pylons

Aircraft pylons are designed in certain aircraft configurations to attach the engines to the fuselage or aircraft wings. In military aircraft they can also be used to carry weapons or fuel tanks (Hackett & Schofield, 1992). For a civil aircraft, a pylon is typically used to mount an engine below an aircraft wing or on the aircraft tail section of the fuselage (Loewenstein, Darcy, & Tesniere, 2006; Spofford et al., 1994). Each pylon transmits the forces generated by its associated engine to the structure of the aircraft, and also allows for flow of fuel lines, electrical systems, hydraulics pipes, and air ducts between the engine and the aircraft (Martinou & Berjot, 2010). A well designed aerodynamic pylon creates the least amount of drag when an imperfect pylon may causes severe problems. One pylon and its engine separated from a 747-200 cargo aircraft right wing some seven minutes after taking off from Schiphol Airport near Amsterdam on October 4, 1992. The consequent investigations (Jonge, 1997; Wanhill & Oldersma, 1996) revealed the fatigue and fracture in the pylon caused the catastrophic accident. Similar accident happened on May 25, 1979 in Illinois (NLR, 1979).

5.1.3 Reverse Engineering

In engineering, design is not only the actual layout of a desired object, but also the analytical processes used to determine what should be created and how the object should be modified to better meet the requirements (Raymer, 2006). It is the engineering challenge of devising a system, component, or process to satisfy some specified needs (W. Wang, 2011). It emphasizes on creativity, originality, and efficiency. Reverse engineering on the other hand focuses on assessment and analyses to reinvent the original parts, complementing realistic constraints with alternative engineering solution. It is the process of analyzing a subject system to identify the system's components and their interrelationships, and create representations of the system in another form or at a higher level of abstraction (Chikofsky & Cross II, 1990; Cross II, Chikofsky, & May Jr., 1992; Waters &

Chikofsky, 1994). Reverse engineering is a top-down reinvention process, while machine design is a bottom-up creation process (W. Wang, 2011).

For centuries, reverse engineering has been a challenge for people who want to understand a product or a phenomena, which finally led to revolution. The reverse engineering of the bird's glide, eventually brought the Wright Brothers' landmark aircraft. The US and USSR put many scientists to reverse engineer the German's V-2 rocket by the end of World War II, to make their own deadly effective weapons (Roland, 1992). These studies have formed the basis of modern day Intercontinental Ballistic Missiles. However, not all reverse engineering projects are successful. Domain knowledge and experience cannot be taken as granted, and are traditionally gained through learning, practicing, summarizing and developing. For a product like an aircraft, the design process is an extremely challenging task due to the complexity, even for a part of it, an aircraft pylon for instance.

The challenge for reverse engineering depends on how to reproduce the "same" object with better or equivalent functionality at lower costs (W. Wang, 2011). To ensure a successful reverse design, great attention to details and accuracy of all measurements is required, in addition to a thorough understanding of the functionality of the original parts (W. Wang, 2011). Reverse engineering is difficult. For example, three major aircraft engine manufacturers renowned worldwide – General Electric (GE), Pratt & Whitney (PW) and Rolls Royce, and there are so many books giving very detailed explanations on how to design an aircraft engine. However many companies and countries tried to produce their own engines through reverse engineering, but most of them failed to face the challenge. Reverse engineering of mechanical parts requires extraction of sufficient information from a particular part to replicate it using appropriate manufacturing techniques (Thompson, Owen, de St. Germain, Stark, & Henderson, 1999). Unfortunately, valuable information is not easy to access, especially CAD files and material specifications. In some situations, given sufficient information, the out-dated technology and techniques set a bar to prevent the reverse engineering from succeeding. As a matter of fact, the complexity of engine design that involves many disciplines and a wealth of design experience, may present failure in one aspect results in failure of the whole reverse engineering project. However, the invention of digital technology has fundamentally revolutionized reverse engineering and it makes mechanical reverse engineering easier in certain aspects.

3D scanners like ATOS III, Konica Minolta Range7 (W. Wang, 2011), are able to provide sharp and high accurate 3D measurement data of an object. Techniques like mass spectrometry, atomic emission spectroscopy, electron specimens interaction and emission, X-ray analysis could be used to identify material elements under certain alloy designation systems (UNS, British Standards, German DIN, Chinese GB, etc.) W. Wang (2011), but there is still much to be learnt. Nowadays, reverse engineering is not limited to hardware anymore, and software rises as another critical aspect (Müller et al., 2000; Ozcan & Morrey, 1995; Selfridge, Waters, & Chikofsky, 1993; Tonella, Torchiano, Du Bois, & Systä, 2007). The integration of both hardware and software makes reverse engineering even more difficult. After Apple CEO Steve Jobs revealed the first iPhone on January 9, 2007, many companies tried to produce similar products. However, for a fairly long time, even though many companies were able to carry out a reverse engineering of the product and launched seemingly identical smartphones, the operability and user experience were far from the mark. This was probably due to the number of genuine breaktroughs demonstrated with hundreds of patent applications related to the technology behind the iPhone (Ishimaru, 2011-04-20).

5.1.4 Design and Reverse Engineering of Pylon Design Process

The personnel in this case study were divided into two groups. On one side, a graduate student from the Concordia University conducted design and reverse engineering of a pylon at a conceptual level for 20 hours per week. A professor from the Concordia University who is an expert in design theory provided the EBD methodology to guide the student to conduct the practice. The professor and the student scheduled a face-to-face meeting every Monday, to make sure the EBD methodology had been correctly carried out. The second group, composed of researchers and aircraft design specialists from École Polytechnique de Montréal and École de Technologie Supérieure evaluated the results thereafter. Their experience spans many collaborations with different aerospace companies over the years and they have been collectively supervising the capstone aircraft pylon design project for several years. As a result of their evaluation, the reverse engineered pylon design knowledge was compared to the product design knowledge digested by normal students in this project. Not until the evaluation stage were there communications between the student from the Concordia University and the expert team.

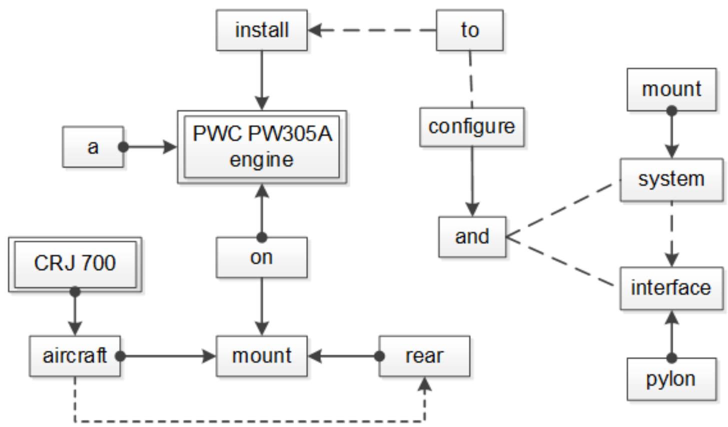

Figure 5.1: ROM diagram for the objective.

Pylon Design and Knowledge Acquisition

For the pylon design, the reverse engineering started with one sentence of the Statement of Work of aforementioned project: `Configure mount system and pylon interface to install a PWC PW305A engine on a Bombardier CRJ 700 aircraft rear mount.`

Environment Analysis

Generic Questions

Based on Figure 5.1, Environment Analysis can be initialized by asking genetic questions. Rules on how to ask generic questions are defined in M. Wang and Zeng (2009). As can be seen in Figure 5.1, there are two most constrained objects i.e. `PWC PW305A engine` and `mount`. An object should be picked up to to start with, according to Rule 2 for objects analysis in M. Wang and Zeng (2009) – "An object with the most undefined constraints should be considered first." Since the object `PWC PW305A engine` is the most constrained and the object `mount` is a part of its constraint, a generic question is asked:

(1). *What is a PWC PW305A engine?*

A PWC PW305A engine is a turbofans engine for mid-class jets, see Figure 5.2. (*The load, operation status and included subsystems/features for this engine need to be clarified from a detailed engine specification/manual, namely, the OEM specifications*).

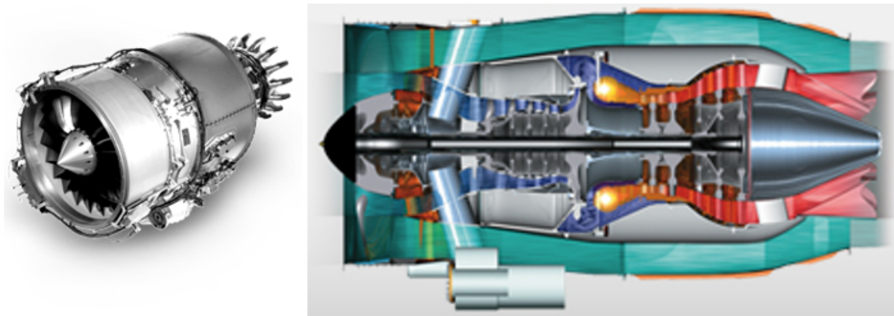

Figure 5.2: The PW305A engine P&WC (n.d.).

After this question, the ROM diagram is updated and simplified with the answer, shown in Figure 5.3). As can be seen, the most constrained object is `PWC PW305A engine`, and some of its constraints are not clear. The object `OEM specifications` is chosen to be clarified. However, the documents are not accessible due to intellectual property, thus needs more investigation from other sources. Therefore, it is underlined in the ROM diagram. Following the same procedure, questions can continually be asked with respect to the unclear objects. Some of the questions regarding the objects shown in the ROM diagram are summarized as follows:

(2). *What is a Bombardier CRJ 700 aircraft?*

A Bombardier CRJ 700 is a Commercial Regional Jet aircraft produced by Bombardier.

(3). *What is an aircraft mount?*

The mount is interface used to connect the engine to the fuselage.

(4). *What is a mount system?*

It includes a frame structure to holds the engine to the pylon, and a frame system attaching the pylon with engine to the fuselage. In addition, it includes other systems that pass through the pylon and the interfaces that transfer control and sensory signals and resources.

(5). *What is a pylon?*

The part of an aircraft's structure which connects an engine to either a wing or a fuselage though the mount system Spofford et al. (1994) (*engine-to-fuselage in this case study*). The

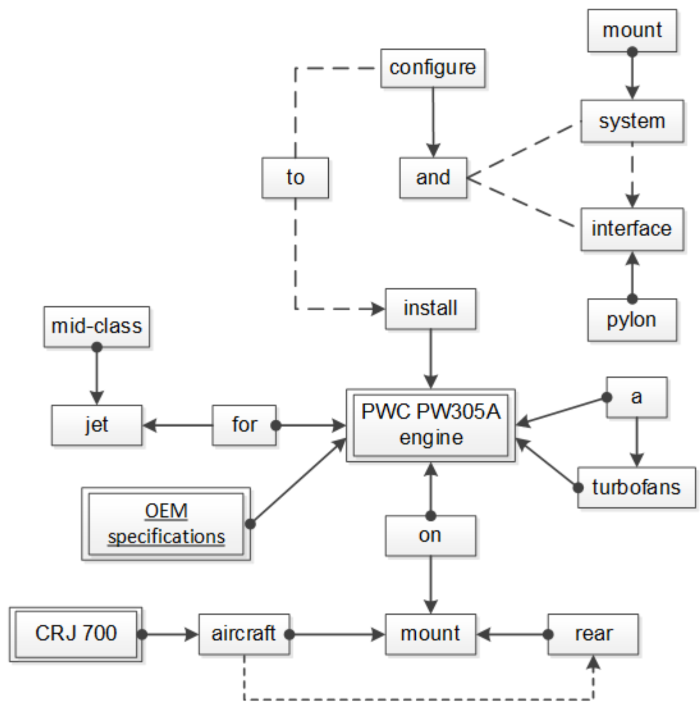

Figure 5.3: The ROM diagram after the first generic question.

major components may include but are not limited to forward engine mounts, aft engine mounts, skin, inner structures (mid-spars) Jonge (1997); Spofford et al. (1994).

(6). *What is pylon interface?*

An interface allows internal mechanical systems (fuel, hydraulics and air systems) or/and electrical systems to pass through Martinou and Berjot (2010); Moir and Seabridge (2003).

(7). *How to install?*

Connect the pylon to fuselage mount, and wire the necessary systems through pylon interfaces (OEM Specification).

(8). *Who to configure?*

Designers/design team.

(9). *How to configure?*

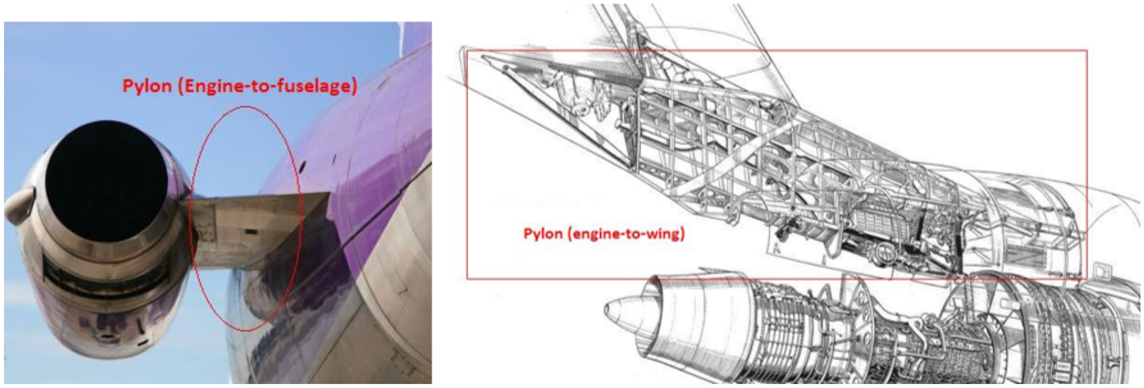

Figure 5.4: A pylon connects an engine to a fuselage (Boeing 727) or to a wing (Boeing 747).

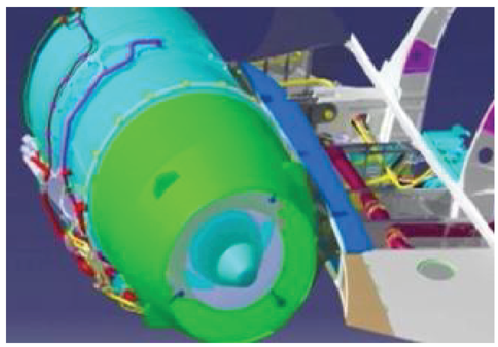

Figure 5.5: The released partial blueprint (McGill, 2010).

Simple and lightweighted construction structure with very little or no aerodynamic penalty (Hackett & Schofield, 1992).

With the generic questions along with the released partial blueprint (see Figure 5.5) of the original project, many answers could be derived, and the most updated ROM is shown in Figure 5.6.

Domain Specific Questions

After the generic question phase, domain specific questions regarding its life cycle are asked. According to the roadmap mentioned previously, the life cycle of a pylon can be divided into nine events as shown in Table 5.1. Since it is so complex and error sensitive for its success, Standard Operating Procedures (SOPs) are involved in each step to reduce impacts from human errors.

Conflict Identification and Solution Generation

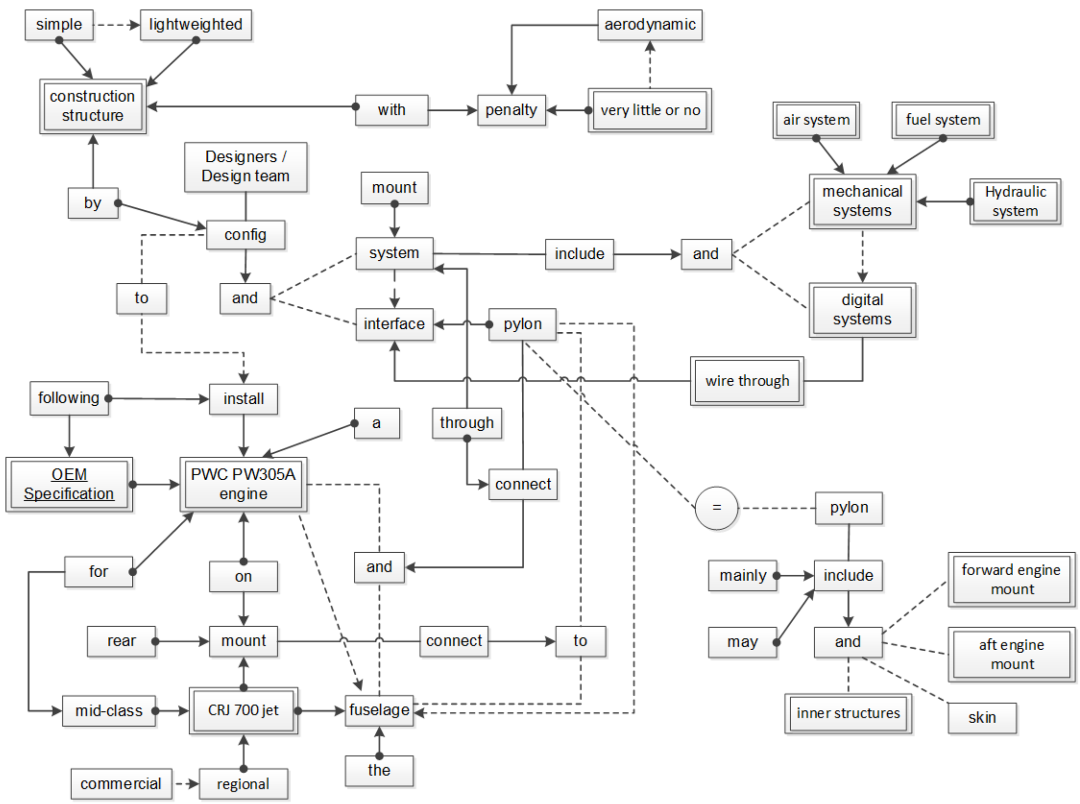

Figure 5.6: Updated ROM diagram for the objective.

Table 5.1: Lifecycle analysis of the pylon design problem.

Event	Natural	Built	Human
Design (Designer)	N/A	CATIA V5, Structure of the Engine, Structure of the rear fuselage	simulation, dynamics, human error may be involved
Manufacture (Programmer)	material may present unwanted physical chemistry process (crack, corrosion, becoming fragile, etc.) in certain conditions	Regulations (FAR, JAR, etc.), Budgeted, Manufacturing SOP, Resources	(Q/A) Quality Assurance, packaging
Transportation (Worker)	Weather varies	Transportation SOP (load & unload rules), means of transportation specialized vehicle/train/airplane/ship	certificated manager
Assembly (Technician)	material may present unwanted physical chemistry process (crack, corrosion, becoming fragile, etc.) in certain conditions	Installation SOP, Verification SOP	Follow the SOP
Test-run (Pilot)	Fly in troposphere (weather varies, atmospheric corrosion, flying objects (birds, flights, etc.)) and stratosphere ($-56\,^{\circ}$C), high-temperature ($950\,^{\circ}$C maximum) for the engine when operating, huge load when taking-off and landing, material may present unwanted physical chemistry process (crack, corrosion, becoming fragile, etc.) in certain conditions, material deficiencies	Regulations (FAR, JAR etc.), airline policy, flight laws & rules, rotor burst (NPRM, 1989) may occurs and damage the pylon	Follow the rules and regulations, human error may be involved
Sales (Salesman)	N/A	Existing similar products in the market	Marketing strategies
Use (User)	Fly in troposphere (weather varies, atmospheric corrosion, flying objects) and stratosphere ($-56\,^{\circ}$C), high-temperature ($950\,^{\circ}$C maximum) for the engine when operating, huge load when taking-off and landing, material may present unwanted physical chemistry process (crack, corrosion, becoming fragile, etc.) in certain conditions, material deficiencies	rotor burst (NPRM, 1989) may damage the pylon, DFDR, 20-year lifecycle, flight laws & rules	Emergency (fire, pressure drop, losing power, etc.), exception-handling guidance, error-detectable, human error
Maintenance (Technician)	Human factor may result in severe problems (W. Wang, 2011)	Regular inspection and maintenance (Lombardo, 2009), Maintenance SOP	Follow the SOP, assembly & disassembly, replace the damaged module, improper maintenance procedures may lead to failure of the pylon's structure (Komarniski, 1998), human error
Disposal (Technician)	Materials may be hazardous	Disassembly & classification SOP	protection may required

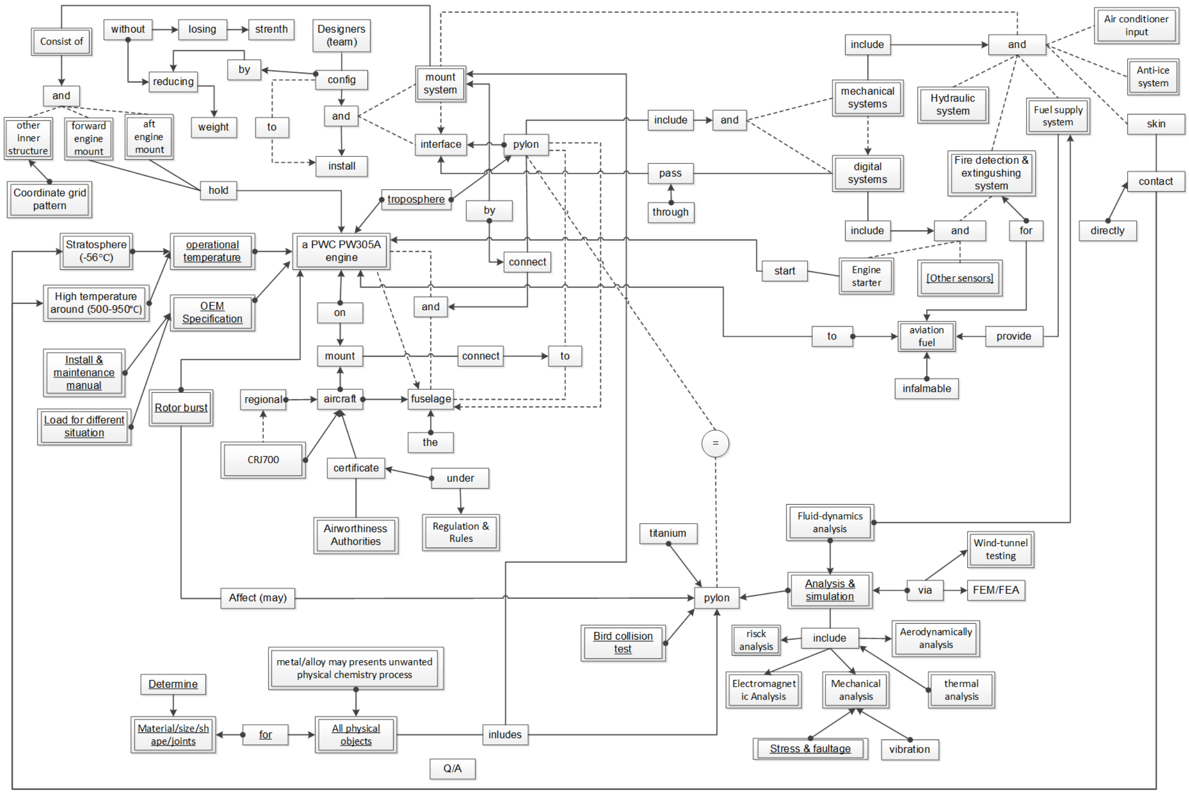

Figure 5.7: The updated ROM diagram after the second iteration.

The most challenging part of the EBD is the Conflict Identification. In (Zeng, 2011, 2015), three formats exist in a ROM diagram. According to the latest ROM diagram (Figure 5.7), some of the major conflicts (not all) are listed in Table 5.2.

For each conflict, many solutions could be feasible. When choosing a solution, multi-criteria decision-making techniques (Kalsi, Hacker, & Lewis, 2001; Kirby, 2001) may have to be applied. This is beyond the scope of the case presented in this section, and is therefore not emphasized. According to the rules defined in (M. Wang & Zeng, 2009; Zeng, 2015), a conflict resulted from natural environment should be solved first. Thus, conflicts 1–5 should be solved first. For the number 1 and 4 conflicts, the temperature profile about the high temperature area was not able to get from the OEM Specification, they were revealed from other resources such as released US patents: “The temperature profile from the front fan section of a jet engine through various compressor sections, the combustion chamber, and the turbine section might change dramatically from the ambient temperature rising to as high as 1500 °C and then cooling down to 300 °C, depending on the engine and

Table 5.2: Major conflicts identified from the most updated ROM diagram.

#	Conflicts	
1	skin directly contacts stratosphere ($-56\,°C$)	skin directly contacts high temperature area around (max. $950\,°C$)
2	inflammable aviation fuel	high temperature area around (max. $950\,°C$)
3	skin directly contacts troposphere	weather varies, atmosphere corrosion, flying objects
4	metal/alloy (perhaps) for all physical objects & Q/A	material may present unwanted physical chemistry process (crack, corrosion, becoming fragile, etc.) in certain conditions
5	rotor burst	material may present unwanted physical chemistry process (crack, corrosion, becoming fragile, etc.) in certain conditions
6	many human works (designer, pilot, technician, etc.)	subject to human errors

aircraft models (W. Wang, 2011). For the PW305A engine, the inter-turbine temperatures limits are $785\,°C$ for maximum takeoff and continuous running, but as high as $950\,°C$ for about 2 seconds at starting transient (FAA, 2003)." Thus for any solution regarding the material of the parts, especially those in contact directly with the engine (forward engine mount, after engine mount, skin, etc.), have to possess refractory properties. For the skin, its material should be considered under thermal test. Similarly, a conceptual solution with multi-criteria to conflict 2 includes fluid pipe sealing, fluid-dynamic analysis and a fire detection & extinguishing system, anti-ice system, bird collision test. For conflict 3, low temperature resistance material, anti-ice system, anti-corrosion coating and material, analysis & tests (electromagnetic test, bird collision test, stress & fatigue test) should be included. For conflict 5, we can either demands engine provider to solve it or built a protection device. The SOPs, error detection & warning systems and automatic flying systems are likely to solve conflict 6.

Since the operational temperature has been found, and with the partially released blueprint available (Figure 5.5), an attempt has been made to infer proper materials for the structural components. For the internal structure of the pylon, it is essential to design a firewall and a bleed air system to regulate the high pressure and high temperature air from the engine's low pressure and hight pressure ports, so that the air wont create a unconformable environment for passengers and damage other systems. To choose the materials, their mechanical properties (stress, shear stress, fracture strength, toughness, forming, etc.), gauge selection, and manufacturing process are to be considered. For the components that are in direct contact to the engine box (forward mount, aft mount, firewall, etc.), titanium alloys should be chosen due to their light weight and temperature resistance, aiti-corrosion properties. Margetan (2002) gave a comprehensive study on titanium alloys studies under the support of FAA. Another comprehensive study was given by Donachie (2000) on titanium and it alloys. From the information given, TA15 or TA17 are seem to be the appropriate choice for this case. However, the geometry parameters are to be determined with further information, e.g., the drag, strength, toughness, etc.

The three activates of the EBD, namely, environment analysis, conflict identification, and solution generation, are conducted recursively until no more unacceptable conflicts exit. However, in this practice, it is so difficult for the student to step further into detail design without specifications on hand and advanced knowledge in the required domains. The described variables cannot be quantified, e.g., determining the margin of the load to mounts, determining the diameter of a fuel pipe from the consumption of the engine, the surface shape of the pylon that smoothly connects the side nacelle and the fuselage, etc. Therefore, the work focused on the conceptual design activities with a few further investigations that are seemly easier. This is a demonstration of what kind of information should be further referenced to refine the requirements, even without direct information source.

5.1.5 Summary of the Work

Based on the results above, conceptual design sketches of the pylon is shown in Figure 5.8. For its shape, we can borrow the idea of airfoil deign without flap from (Raymer, 2006) to form the pylon style. Here, drag should be considered primarily to a better aerodynamic performance. The action plan for pylon design was systematically categories into five levels, namely, project management, detail design, manufacturing, system integration, and service after launch, in terms of their work contents and required resources. However, due to the page limitation, they are not included in this

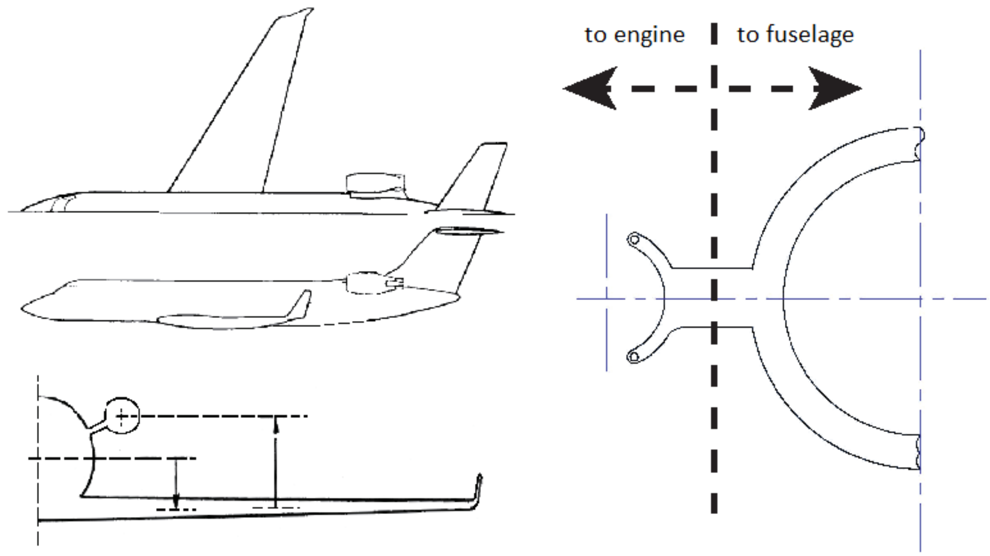

Figure 5.8: Conceptual sketches of the of the aircraft pylon and a forward mount configuration. Inspired by Boppe (1987).

subsection.

For any system design, quality control and improvements are critical. Either from system design perspective or reverse engineering prospective, it is a constant recursive process throughout the product life cycle (Blanchard, 2004; Mitra, 2008), the spirit of the EBD methodology as well. Thus, technical reviews are compulsory within the process to guarantee the feasibilities and correctness of a design. Through the presented analyses and action plan, the pylon design procedure is abstracted in quality assurance and performance satisfactory regards. The work flow for the pylon design regarding its life cycle is derived and simplified in Figure 5.9. This process is perhaps a generalized process applied to an aircraft design as well. Some other major activities (Hale, 1984; Moir & Seabridge, 2003; Wanhill & Oldersma, 1996) related to the detailed pylon design, e.g., system modelling and optimization (structure & systems), metallurgical testing, assembly and verifications, software system (fire, stall, test-run), wind tunnel & simulator testing, air carrier maintenance procedures, reporting & surveillance procedures, manufacturer's production and procedures, airworthiness test & test fly, DFDR (Digital Flight Data Recorder) readout, are not discussed in this section. There are other concerns which are not related to pylon design itself but related to aircraft design, for example Noise and Emission Control (FAA issued regulations for it) for the environment

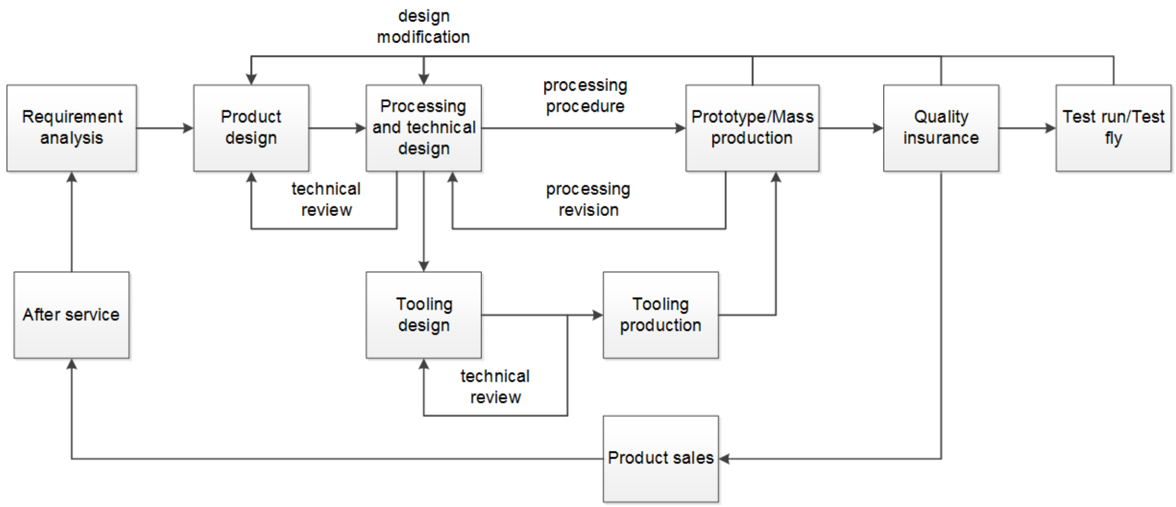

Figure 5.9: The derived pylon design process in terms of its product life cycle.

impact, are not put in the contents as well.

Thanks to the digital mock-up that the CAD/CAM software (CATIA, SolidWorks, ANSYS, etc.) provides, not only the 3D drawings of components and their assembly could be digitalized, but also their analysis and optimization could be virtually tested. The software facilitates the design process since many steps could be conducted simultaneously through collaborations among different groups/departments. The consequences resulting from design modification to the design in terms of performance, cost, process and risk could be predicted before production.

Once a draft pylon design is established, optimization is another task to perform to test and improve the design. As a guideline, there are several major objectives to be achieved in terms of operational research. For objective functions, we have to minimize: (1) Drag at the cruising condition, (2) shock strength near engine-pylon junction, and (3) structural weight of the pylon. And they are subject to the constraints including: (1). Load and stationary condition and cruising condition, (2) strength margin, (3) inter-spar heights and weight, and (4) thermal margin.

Table 5.3: Pylon design at project management level.

Work	Content	Tool/Resources
Objective and requirement definition	Objective definition, requirement identification	MS Office Excel/Word or PDF
Document and resource management	File name, category definitions	ERP/PLM system
Meeting and workload assignment	Discuss and assign partners their work and process report	N/A
General roadmap	General deadline and budget assignment	N/A
Coordinate and meeting	Set inter-partner coordinator(s), define resources accessibility among partners	N/A

5.1.6 Evaluation

In order to evaluate the value of the EBD methodology to support the reverse engineering approach detailed in this section, the aircraft design specialists used fundamental engineering reasoning criteria based on critical thinking concepts and tools (Paul, 2006). This set of criteria is typically used in a methodical approach to analyze the structure and completeness of engineering artifacts (documents, designs, tools, etc.).

The experts therefore compared the results documented in the reverse engineering case study with their experience and years of observation of the actual pylon design performed by the aerospace engineering students. The evaluation is summarized in Table 5.8.

Overall, the case study was very well received and the results show many promising avenues for future work. Some of the supervisors also suggested that the approach would be useful for instructors when teaching with a project based learning approach such as the capstone project presented in this section. Indeed, an EBD analysis could provide the teaching staff with some pointers as to which knowledge areas to focus their coaching on by looking at the identified conflicts that the new design brief infers.

Table 5.4: Pylon design at detail design level.

Work	Content	Tool/Resources
Fuselage mount understanding	Connect mount, I/O systems	OEM specifications
Engine specification understanding	Mount, interface, I/O systems	OEM specifications
Design roadmap plan	General structure design (modularized) and workload assignment for each member, schedule meetings	MS Office Excel/Word or PDF
Components decomposition with assembly joints	Structural design, 3-D drownings of component, inner system configuration, interfaces for inner systems, inner system design, component supplier comparison and selection	CATIA, component supplier
Virtual assembly and analysis	structural analysis, weight analysis, thermal analysis, risk analysis, conjunction analysis, stress analysis, fluid dynamics analysis, electromagnetism analysis (Kundu, 2010), aerodynamics analysis for the pylon, optimizations	CATIA, AFC (ABAQUS for CATIA) (ABAQUS, 2007), ANSYS (An & Li, 2007), FEM/FEA (Wanhill & Oldersma, 1996)
Technology review [and refined/redesign]	To verify the design, feasibility and economic analysis	N/A
Verification and final design report	What/how/why are the design components and their 3D-drawings, analysis results, costs estimation, suggestions for production	MS Office Excel/Word

Table 5.5: Pylon design at manufacturing level.

Work	Content	Tool/Resources
Resource management	Equipments, materials	ERP/PLM system
Prototype and testing	Materials selection and evaluation, metallurgical and mechanical testing (stress testing and fatigue testing)	Specialized equipments and procedure
ERP/PLM system	What/ why/how are the testing and results, costs, rules/suggestions for storage, transportation and mass production, cost assignment, problems if there are	MS Office Excel/Word or PDF
Technical report and procedure for mass production		
Meeting and improvements	deliverability	
Mass production	Pylon production	Manufacturing SOP
QA and certification	Product inspection	Specialized equipments, Inspection/Pass Criteria Manual
General roadmap	General deadline and budget assignment	N/A
Packaging	Pack the pylon products for transportation and/or assembly	Specialized equipments

Table 5.6: Pylon design at system integration level.

Work	Content	Tool/Resources
Simulation and analysis	vibration analysis, linear and nonlinear response to steady-state and transient stress analysis (Hale, 1984), aero-performance for each module (engine, pylon, fuselage, etc.) and their matching analysis, overall aero-performance analysis and optimization, instability analysis, electromagnetism analysis	CATIA, AFC (ABAQUS for CATIA) (ABAQUS, 2007), ANSYS (An & Li, 2007), FEM/FEA (Vandeventer, 2007; Wanhill & Oldersma, 1996)
Assembly and verification	System integrations	Assembly and Maintenance SOP
Wing tunnel and simulator testing	bird-collision test, crash-test, airworthiness test, aerodynamics, failure analysis, validate analysis in simulation	CATIA, AFC (ABAQUS for CATIA) (ABAQUS, 2007), (An & Li, 2007), (Vandeventer, 2007; Wanhill & Oldersma, 1996)
DFDR (Digital Flight Data Recorder) Readout and analysis	Data analysis to verify system integrity	N/A
Mass production	Pylon production	N/A
Test fly and DFDR result analysis	Airworthiness test and record analysis in real situation	N/A
Reports generation	Operational manual, maintenance SOP	N/A
Certifications	Certifications from airworthiness authorities (FAA, JAA, etc.)	Airworthiness Authorities (FAA, JAA, etc.)

Table 5.7: Pylon design after launch.

Work	Content	Tool/Resources
Business operation	Commercial operation and flight log	Well trained flight crew
After maintenance	Regular & emergent maintenance	Maintenance SOP
FAR/FAA Reporting and Surveillance Procedures	Periodic readout and analysis of Digital Flight Data Recorder (DFDR) data, Collaborative investigation if any critical failure happens	Regulations and ules
Meeting and workload assignment	Discuss and assign partners their work and process report	N/A

5.1.7 Discussion

The verdicts from the experts are inspiring. It was unexpected at the beginning of the practice. For such a complex project, it was seemly impossible for a novice within a short time frame, especially starting with one sentence only. The student was initially overwhelmed by the huge amount of information available. When starting with the EBD methodology, the student was able to identify the critical resource to conduct his practice step by step. Apart from the results presented in this section, other work, such as stress distribution analysis and drag computation at subsonic and transonic speeds of an aircraft pylon, were not completed within the time frame, and therefore were not presented here. Though the final results may seem simple for experienced designer, the attempt and the path that lead to a promising future work can be observed.

5.1.8 Conclusions

The EBD methodology was applied to an aircraft pylon design project from a reverse engineering based approach, within one month for a graduate student who did not have any knowledge in aerospace. The objective is to evaluate how much knowledge could a novice had assimilated within a short time span. Experts were then invited to assess the results. According to the evaluation, the experts gave an overall positive and inspiring verdict. The problem was well understood, and a few design concepts and specifications were well addressed. In other words, the effectiveness of the

Table 5.8: Evaluation from experts.

c

Elements of thought in engineering reasoning (evaluation criteria)	Expert Verdict	Expert comments	Examples
Establishing purpose	N/A	The purpose is established by the existence of a statement of work	N/A
Understanding the problem	Outstanding	The conflict identification step of the EBD methodology produced surprisingly accurate results. Some of these conflicts are only recognized by novice designers late in the design process.	Critical temperature envelopes at different stages of a given flight path
Identification of assumptions	Good	Most assumptions were well justified in the case study and their criticality was well established.	Material failure due to manufacturing process
Specification of viewpoint	Good	The various stakeholders are well established and their roles are understood in the design process	Certification bodies and role of standards. Process understanding
Data, information and evidence	Average	One of the great challenges and particularities of aircraft design is the overload of information at an engineers disposal. Some data is indeed available to the general public but IP concerning testing and aerodynamic profiling for example prevents most of the wealth of data to be visible to non-professionals.	Aerodynamics and testing data
Concepts and theories	Good	The concepts and theories behind aircraft design are well established and the body of knowledge is widely accessible. These were none the less correctly reutilizes	Use of computer tools to perform specific simulations
Inferences	Limited	In such complex systems the interpretation of the design choices is a very difficult analysis even for experts. Here some of the interpretations made showed the lack of knowledge concerning the particular business aspects governing the statement of work.	Rotor burst prevention and partner responsibility
Implications and consequences	Outstanding	The ROM diagram was a view that could be used by experts to focus on strategic impact analysis of design choices	Overall ROM diagram

EBD methodology has been validated. It is concluded that EBD is capable of providing a systematic process on extracting key components and their relationships, and inferring critical recourses required for the a further step. It enables a designer to find out the implicit requirements by considering the product life cycle, which reduces the possibility of defective design caused by lack of global control for a designer and therefore contributes much to propose a good solution.

5.2 Software Design Application - Enterprise Application Integration[2]

5.2.1 Introduction

Along with the rapid development of information technologies, various applications have been developed in almost every aspect of enterprise business processes such as Supply Chain Management (SCM), Customer Relationship Management (CRM), Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), in order to enable organizations to improve their use of information systems (IS) in supporting their operational and financial goals (Ma, Duval, & Rui, 2009; Puschmann & Alt, 2001; Scheibler, Mietzner, & Leymann, 2009). A SCM application focuses on coordination and inter-enterprise supply chain upstream and downstream relationships (Ma et al., 2009). A CRM application supports organizations to improve their front-end operations regarding the value they offer to their customers (Kevork & Vrechopoulos, 2009). An ERP application is a software package that attempts to integrate all the organizations' departments and functions into a single system to serve the departments' needs (Botta-Genoulaz & Millet, 2005). Most of these applications have been built with very specialized focus on specific business needs, and are often developed without thorough consideration of how to share with other existing applications. With such a great quantity and variety of applications, there is a growing need for facilitating the data sharing among them. Each individual application is often upgraded independently from others that might be developed by different IT companies. As a result, different applications with the similar functions or several generations of the same application, may co-exist in an enterprise. Inefficient data sharing among those applications in a business process inhibits seriously the productivity of the enterprise. This situation is mostly due to the complexity and the multi-disciplinary nature of the business processes (Linthicum, 2000). It was estimated that more than 30 percent of IT dollars were spent to link different systems together (Linthicum, 2000). The IT industry has been trying to bring competitive advantages to businesses by working on various Enterprise Application Integration (EAI) solutions. It is a challenging task to integrate an individual application into other application platforms in a manner that fits into the general business logic existing in an enterprise.

EAI has emerged to address the demands of horizontal and vertical integrations, within and

[2]The content of this section has been published as a journal paper in (Tan et al., 2012)

beyond enterprises, in more flexible and maintainable way (Johannesson & Perjons, 2001; Themistocleous, 2004). Irani, Themistocleous, and Love (2003) stated "EAI addresses the need to integrate both intra and inter-organizational systems". This can be achieved by incorporating functionality from different legacy applications in use. Linthicum (2000) defined EAI as "unrestricted sharing of data and business processes among any connected applications and data sources in the enterprise". Du, Peng, and Zhou (2008) considered that "the integration of applications enables information sharing and business processes, both of which result in efficient operations and flexible delivery of business service to customers. D. Chen, Doumeingts, and Vernadat (2008) gave a similar definition to enterprise integration as "enterprise integration is the process of ensuring the interaction between enterprise entities necessary to achieve domain objectives". D. Chen et al. (2008) indicated that enterprise integration can be approached in various manners and at various levels, such as: (1) physical integration (interconnection of devices, NC machines via computer networks), (2) application integration (integration of software applications and database systems) and (3) business integration (co-ordination of functions that manage, control and monitor business processes). The scope of implementing EAI can be classified into three major components according to (Irani et al., 2003): (1) intra-organizational component, which integrates packaged and custom systems, (2) inter-organizational application integration, which incorporates cross-enterprise business processes and systems throughout a supply chain, and (3) hybrid application integration component, which integrates business-to-customer applications with other inter-organizational solutions. The major business objectives of EAI implementations are to improve productivity, to facilitate data sharing, to achieve greater agility and flexibility in supporting business processes integration, to avoid trusted legacy systems replacements, and to solve the issues related to organizational mergers. In this case study, integrations from all levels are considered as a whole enterprise-wide application integration problem.

The research conducted in the EAI area emphasized on many issues, including the semantic and syntactic issues, the analytical issues, and the technical issues. In Liu *et al*'s state of the art review (X. Liu, Zang, Radhakrishnan, & Tu, 2008), they discussed the EAI from two generic points of view: semantic and syntactic integration. In their review, they concluded that the current EAI solutions do not satisfy the manufacturing companies' needs, and that organizations should focus more on semantic integration. Sharif, Elliman, Love, and Badii (2004) proposed an EAI impact framework to address research challenges in EAI area. However, the framework itself is complex and is hard to implement for an EAI solution. Themistocleous Themistocleous (2004) classified the major EAI drivers to eight major factors: barriers, benefits, costs, external and internal pressures, support, IT sophistication, evaluation framework for integration technologies, and assessments of EAI packages and IT infrastructure. Compared to (Themistocleous, 2004), Lam (2005) investigated the critical success factors for EAI from administrative perspective, and categorized them into three major groups: (1) top management support, (2) overall integration strategy, and (3) EAI project planning and execution. Vasconcelos, da Silva, Fernandes, and Tribolet (2004) verified the dimensions that should be represented as part of Information Systems Architecture of EAI. Scheibler et al. (2009) introduced a platform independent approach to modeling, describing, and enacting EAI patterns in service oriented architecture. Losavio, Ortega, and Pérez (2002) modeled the EAI based on Brown's Conceptual Model of Integration, which was extended to obtain more unified and organized views in EAI by Sandoe and Saharia (1999). Kamal, Weerakkody, and Jones (2009) evaluated the implementation of EAI solutions to Welsh Local Government Association by distinguishing between the factors of adoption and non-adoption of the EAI. Puschmann and Alt (2001) presented an implementation of EAI in Robert Bosch Group and addressed the need for standardized integration architecture. In addition, studies on customized EAI solutions attracted a lot of researchers. For example, Ni, Lu, Yarlagadda, and Ming (2006) proposed a collaborative engine to facilitate application integration for tooling companies. With this engine, both technical and business process integration requirements were satisfied. Also, security issue in information sharing was addressed in the proposed integration solution. While some of the studies discussed the design issues of the EAI solutions, Gleghorn (2005) suggested that the design objectives of the integration solutions are configurable, extensible and reusable. Lublinsky (2001) presented a procedure to design an EAI solution: define and catalog business processes, business events, IT components, process rules and messages, and message contents. Umapathy, Purao, and Barton (2008) proposed a study on conceptual design of enterprise integration solutions, which indicated that there are two main pre-requisites for the design process: an understanding of the design requirements represented in Business Process Models, and the expertise that professionals brought to the project as design knowledge acquired from enterprise integration patterns. Johannesson and Perjons (2001) suggested a methodological support for modeling the alignment of application integration to business processes, and some design guidelines for design, validation and presentation of applications integration were given. It fell into two groups: the first group to assist the designer in obtaining different views of the model while the second group to check the completeness of the process diagram.

Although research has been done for specific problems in EAI, enterprises are still faced with many problems. Enterprises tend to depend on various legacy applications in supporting their business strategies and in achieving their goals by implementing software applications for special requirements of different functional sectors, which are mutually independent at most of the time (Du et al., 2008). Enterprises need to integrate their business functions into a single system, in order to be able to adopt the changes in their environments and in the technology development. Traditional approaches, such as Electronic Data Interchange, database-oriented middleware and distributed objects (e.g. CORBA, DCOM, etc.) technology, do not fully automate the desired integration (Irani et al., 2003; Themistocleous, 2004). Innovative solutions are needed to achieve this goal more easily. It leads to new integration technologies supporting effective EAI solutions such as message brokers, process brokers, middleware systems (e.g. SOAP, J2EE, etc.), adopters, wrapper's API, web-services (e.g. W3C, WebServices.or, etc.). Most of the commercial integration products and services fall into two basic categories: hosted integration solutions and server-based middleware solutions (Du et al., 2008; Gleghorn, 2005; Irani et al., 2003; Linthicum, 2000; X. Liu et al., 2008). There are many EAI solutions in the market such as "Vitrea", "ActiveSoftware", "CrossWorld" and many others (Lam, 2005; Lee, Siau, & Hong, 2003). Meanwhile, many integration tools have been developed by different vendors such as "BizTalk Server 2004" developed by Microsoft, "WebSphere MQ" developed by IBM and several others (Silveira & Pastor, 2006). However, enterprises are forced to give up their legacy applications and invest a huge amount of money to buy those new integrated solutions in order to manage their business. This is not necessarily to be the only option. The reasons lie mainly in three aspects: first, from the implementation point of view, different enterprises may have different EAI requirements, which come from various applications and variety of business data and processes. It is practically impossible to achieve all those requirements in one EAI system (Ni et al., 2006; Umapathy et al., 2008). Different applications need different integration methods. Second, many applications have their own built-in functions for development, e.g. VBA, ActiveX, AutoCAD script, and API for AutoCAD. However, it is often costly and time consuming to integrate enterprise applications by using those built-in functions, which requires not only the understanding of different built-in functions for different systems but also the internal data and process structures within each related applications. Third, most of existing EAI solutions are focused on answering questions such as "what do we need to do to integrate the various applications?" instead of considering the implementation process as the sum of existing applications and the context of the business environment (Linthicum, 2000; X. Liu et al., 2008).

In this case study, EAI problems is discussed from the design point of view. By applying Environment Based Design (EBD) methodology to EAI problems, a framework has been proposed. Through a case study, a low cost and high efficiency EAI solution was developed to validate the framework.

5.2.2 A Framework to EAI Using EBD

Since the purpose of EAI is to *seamlessly integrate various kinds of applications into a business process to increase the employees' work efficiency and to promote the company's business effectiveness*, we start by drawing a ROM diagram as shown in Figure 5.10. The environment analysis

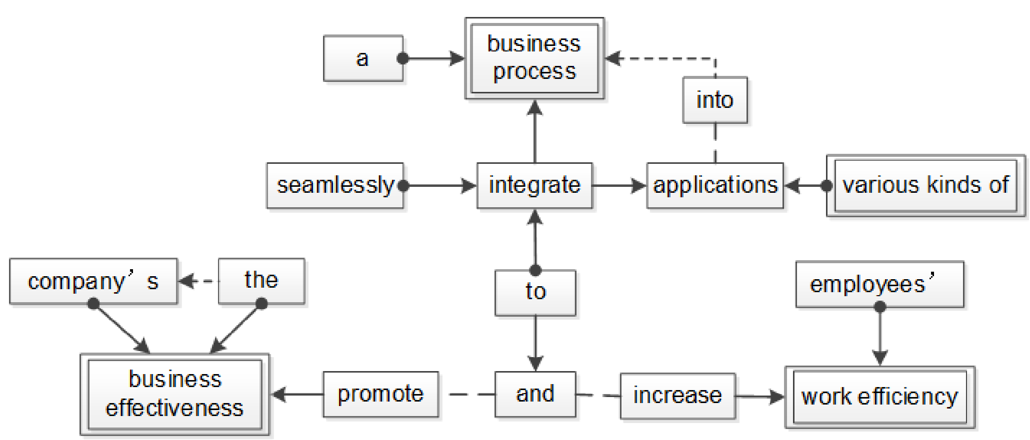

Figure 5.10: The ROM diagram for an EAI objective in general.

will then be conducted based on the initial ROM diagram. Obviously, "*integrate*" is the most constrained object as a predicate relation is a bi-directional constraint. According to the rules defined in (M. Wang & Zeng, 2009), questions will be asked firstly about its constraining object that has the most constraints. In this case, they are "*business effectiveness*", "*work efficiency*", "*applications*", and "*business process*". By applying the same rules, for each one of them, questions are asked as listed in Table 5.9. Those questions have to be answered to narrow down the scope of an EAI case. When answering a question, it is suggested to give a quantifiable or measurable answer. For example, for a question like "*What do you mean by effective?*", an answer with a quantifiable or measurable factor is preferred, e.g., "*A representative is able to process 2 orders in 10 minutes (was 1 in 10 minutes)*".

Table 5.9: A list of general questions asked based on Figure 5.10.

Main Object	Questions to be answered
business effectiveness	What is the the company? What is the company's business effectiveness? / What do you mean by effective? How to promote?
work efficiency	What are the employees? What is employees' work efficiency? / What do you mean by efficient? Why/How to increase?
application	What are various kinds of the applications?
integrate	Why/How to integrate applications to business process? How to integrate to promote? How to integrate to increase? What do you mean by seamlessly?

Once an answer is provided, the ROM diagram is updated accordingly. If every object in the most updated ROM is clear, domain-specific questions will be asked next. Domain specific questions are related to the lifecycle of the product to be designed. For an EAI problem, the final product is an EAI solution. Several events within the lifecycle of a commercial EAI solution can be summarized as design, manufacturing, sales, deployment, use, maintenance, and disposal. For each event, more requirements are collected. With those requirements, the ROM diagram is updated again, and questions are asked based on the new objects. In this way, environment components and their relations can be sufficiently gathered.

Followed by environment analysis, conflict identification will be conducted. According to the general forms for a conflict defined in Figure A.5, along with the pre-defined rules in Section 2, major conflicts could be identified. Analysis of the dependency between the major conflicts will thus lead to the root conflict(s) which will be resolved first. This will be illustrated in the case study.

Since EAI solutions are mostly case dependent, an EAI solution cannot be expected to fit into all the companies. However, the objective of any EAI is the same, which makes a general framework feasible. Back to the generic questions and the roadmap, several indispensable major environment components are: the company, the business process, the employees, maintenance, functions, and human-machine interface. All of those major environment components are indeed connected by the so called workflow in the modern business. The realization of the workflow depends on information/data flow throughout the business process among involved parties/stakeholders (employees, customers, partners, etc.). Ideally, for EAI implementation, a single standard file format such as the Universal File Format (UFF) (Alleman, 2004) would be perfect, which reserves and conveys the necessary information required by all applications. However, it is impossible in real practice due to security reason or business realities. Vendors worldwide have launched software systems that follow particular standard in each domain. That is why aforementioned brokers or adapters in introduction have been developed to bypass the format limitations, or support UFF as an intermediary agent to enable a smooth information/data exchange. In EAI, "*seamlessly*" can be achieved by minimizing the human operations within the workflow, and by replacing them with digitalized information/data flow. In order to provide extendability (maintenance consideration) to an EAI solution, APIs are expected for future integration. It involves domain knowledge in administration, management and information technology in this regard. Thus, a general framework is graphically represented in Figure 5.11. Four layers have been adopted for the framework – a Data Management Layer, an API Layer, a Workflow Layer and a GUI (Graphic User Interface) Layer. The authorized parties can operate any application (hardware or software) to access/send information/data to a single data system regardless of the application type. In this way, an EAI solution is able to seamlessly integrate all applications into the business process.

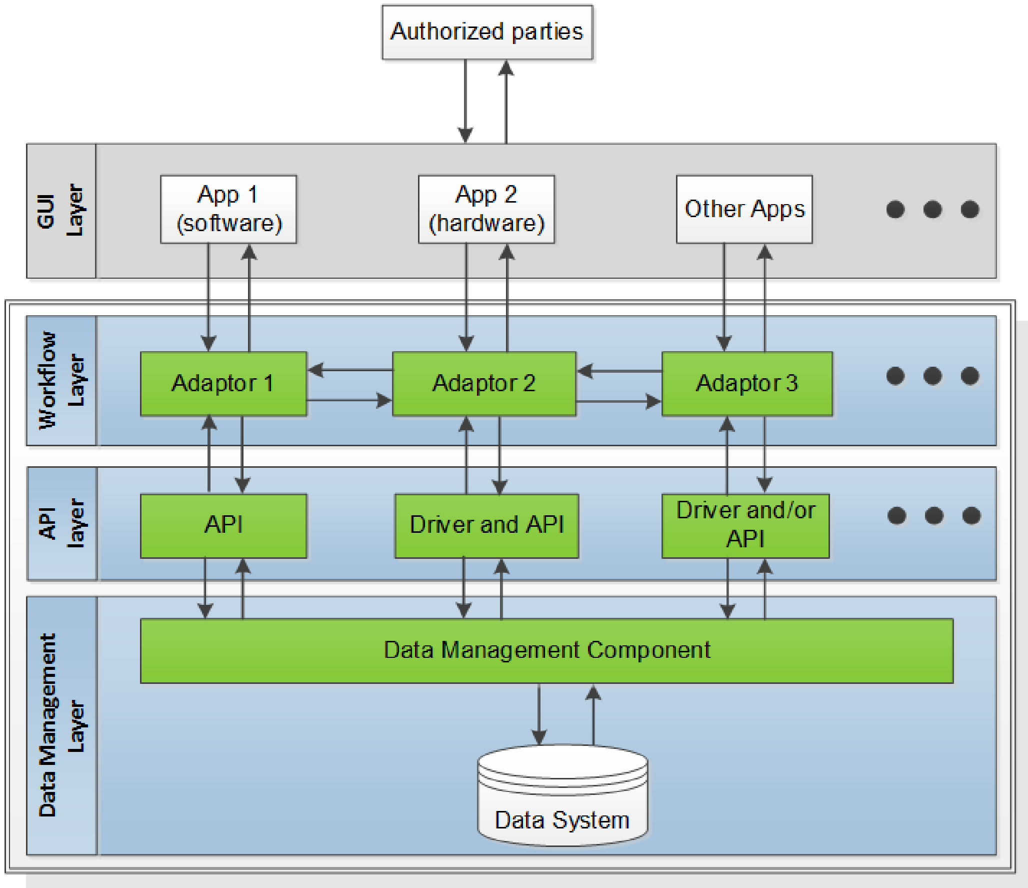

Figure 5.11: A framework for the EAI problems.

5.2.3 The Design Problem

This case study was taken from a metal cutting tool developing, designing and manufacturing company. This company has approximately one hundred employees, and has more than 40-year history in the metal cutting industry. Like many other enterprises with long history, this company had a very urgent demand on integrating different applications they have been using. One of the challenges faced by the company is give all their employees necessary, transparent and real-time access to information needed for achieving their business goals. Many of the legacy applications still in use today were developed by aged and proprietary technologies.

In the past two decades, the company has been constantly investing into enterprise applications to improve its management as well as product design and realization. In the early 1990s, the company was one of the first few in North America to use an early ERP system MAPICS. The system includes Inventory Management, Product Data Management, Production Monitoring, Customer Orders Management, Accounting Management, Sales Analysis and other modules (B. Chen, 2007). Therefore, almost the entire company is managed by this system. Although it is a very old system without friendly user interface, the ERP system has been adapted and combined with the company's business processes in a very high level. It is acting as the heart of the company. Thus if the system stopped working, the company's normal business would be severely interrupted. Although the MAPICS is very powerful, the developer (IBM) has abandoned the software and developed a new ERP system to replace it. IBM can provide data transfer tools if the company decided to upgrade to the new ERP system; however, it cannot guarantee that everything can be transferred properly. Because of this concern, most of the managers of the company rejected to upgrade the ERP.

In addition, many other enterprise applications such as AutoCAD, Word and Excel were introduced for different purposes. Many of the legacy applications still in use today were developed by aged and proprietary technologies. There is not a data sharing framework for those applications. All data tranferring/coverting are implemented manually. As a result, the business processes do not run smoothly within the company. There was an increasing demand of either upgrading their enterprise applications to sophisticated ones, which would cost the company dearly, or integrating the existing applications, which is time-consuming. After some investigations, a comparison between two possible options is shown in Table 5.10. It clearly shows that the best solution for this problem is to develop an EAI solution which can maintain the legacy applications, especially the MAPICS system, and address issues related to these applications.

Obviously, for the concerned company, developing an EAI solution is a better option to make use of the legacy applications and to resolve the problems from the previous analysis. The EAI development can be viewed as a design problem. The objective can be summarized as "Design a solution to integrate the current enterprise applications and to smoothen the business processes". From this one-sentence objective, we can start requirements analysis.

5.2.4 Environment Analysis

A ROM diagram can be drawn as in Figure 5.12.(a) according to the objective. It is clear that "*applications*", "*processes*" and "*solution*" are the current key environment components, since

Table 5.10: Upgrading V.S. Developing an EAI solution.

Problems	Upgrading	EAI
Cost	High (> $380,000 (Aberden Group, 2007))	Low (< $10,000 (B. Chen, 2007))
Better interface of the ERP	Yes	Yes
Affect the current production	Yes	No
Data transfer	Yes	No
Employee Training	Yes	No
Integration of ERP and Office	Yes	Yes
Integration of ERP and CAD	No	Yes
Integration of CAD with other physical devices	No	Yes

they are the most constrained objects in the diagram. Then generic questions about the objects in the ROM diagram have to be asked, according to the question asking rules defined in (M. Wang & Zeng, 2009). For example, we start with the most constrained object – "*applications*": "what are the current applications?" As mentioned above, there are three major types of applications: MAPICS, AutoCAD and MS Office. With the answer, the ROM diagram is updated as shown in Figure 5.12.(b). Then, we can go on to ask a question about the most constrained object in Figure 5.12.(b) – "*processes*": "what are the business processes?" For the company, the business processes can be modeled as shown in Figure 5.13. Generally, there are 12 steps for the company to finish an order, which are listed in Table 5.11.

Although some steps (step 4 and 5, for example) may not be necessary for an order, most of the steps are conducted by employees. This situation will definitely result in many potential conflicts, which will be identified later. With this answer, the ROM diagram is updated again. We can move to another object – "*solution*", just like what we did for the other two objects. The answer to the "*solution*" is summarized as: "cost-effective (budget for $10,000), easy to use (user-friendly interface), reliable (not subject to human error, guarantee data integrity, emergency handling)".

After we finish question asking for the environment components, we should start with the relation objects. If we take "*integrate*", for instance, a question like "how to integrate?" can be asked.

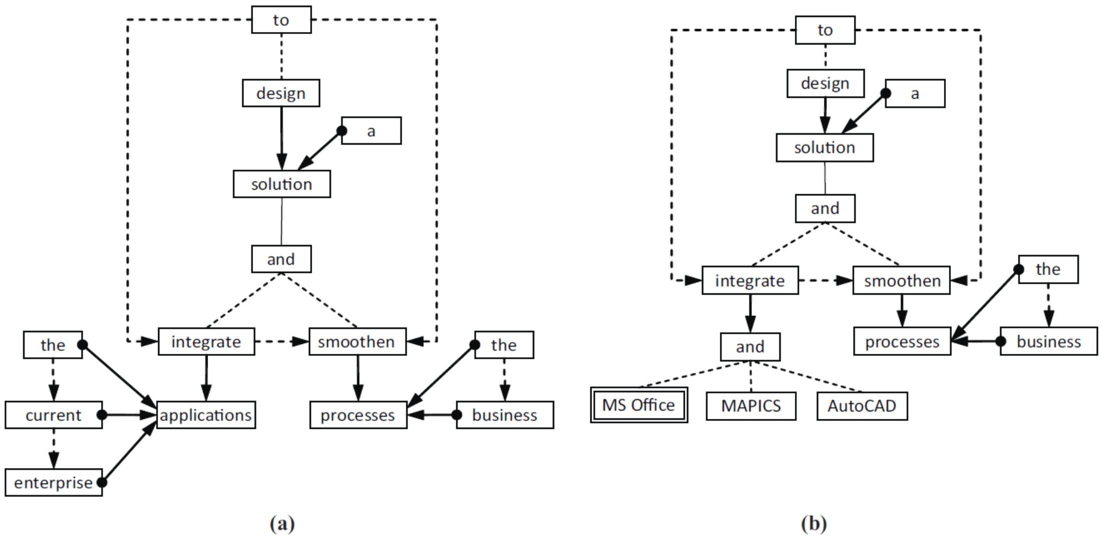

Figure 5.12: ROM diagrams. (a) The ROM diagram for the objective. (b) The updated ROM diagram after a generic question.

To answer such a question, we need specific knowledge, which means investigations have to be made in order to give a good answer. For this case, fully-automated application integration type (Microsoft, 2003) with data structure model is employed to minimize human errors in the business processes. Using this structure, it is not necessary to manage the point-to-point information transferring/converting between two applications. Each application can retrieve data from a sharing database. For the question "how to smoothen?", the company indeed wanted to speed up the whole business cycle and to release the employees from tedious repetitive work, by eliminating unnecessary manual operations. Such a release can eliminate some potential human errors to improve the reliability of the data within the company. As a matter of fact, the answer to "how to integrate?" has partially addressed this question. If we put these two answers back to the ROM, we should further our environment analysis by asking questions like "what are the kinds of data?" In order to answer this question, we have to go back to the three enterprise applications to investigate the types of data sharing required. Table 5.12 shows the features for each application.

The process of asking the right questions, getting the proper answers and updating the environment components continues, until the designer defines all the relevant components to the design problem.

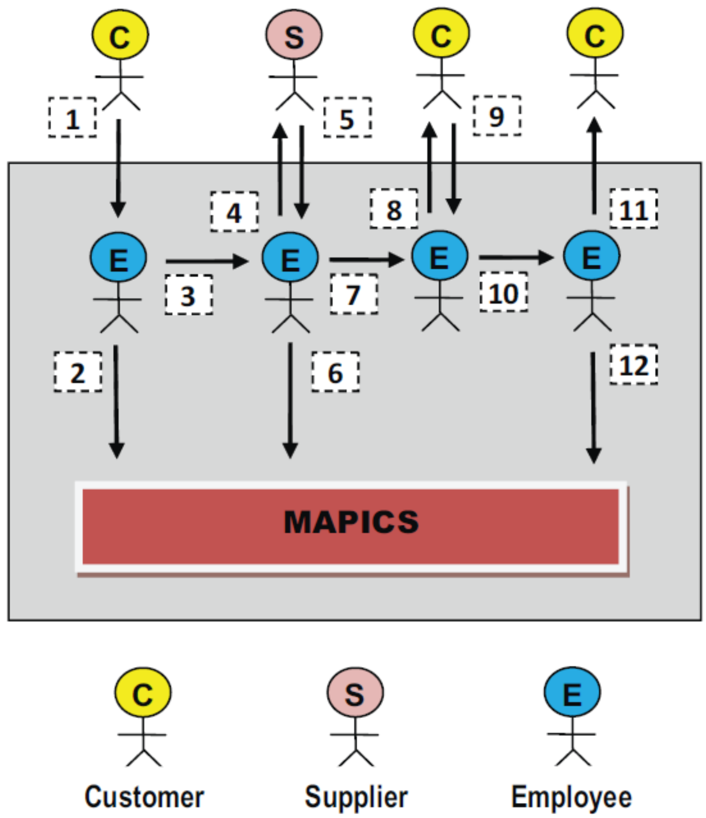

Figure 5.13: A model of business processes for the company.

According to the roadmap mentioned in the Chapter A, since the EAI solution is specialized for the company, its lifecycle is divided into four kinds of events: design, manufacture, use and maintenance. For each event, the requirements are further classified into natural, human, and built environments. The details are shown in Table 5.13. Based on the analysis carried out so far, the ROM diagram can be updated and simplified in Figure 5.14.

5.2.5 Conflict Identifications and Solution Generation

Based on the updated ROM diagram, we are able to identify many conflicts by following the rules given in (Zeng, 2015). For example, in Figure 5.14, for the object "*solution*", it is required to be "*not subject to human errors*". And it is obvious that the "*solution*" includes two branches (indicated by the object "includes"). According to the defined ***Rule 3*** in (Zeng, 2015), the constraint "*not subject to human errors*" also constrains the object "*smoothen*". Thus, for "*smoothen*", we found

Table 5.11: The general business processes for the company.

Step	Description
1	Make an order
2	Create the order to MAPICS
3	Inform the manufacturing department
4	Inform resource suppliers for materials if insufficient in inventory
5	Resource received, manufacture the ordered product
6	Check or update the MAPICS records
7	The ordered product is ready
8	Send bill to the customer
9	Payment received
10	The order is ready to ship
11	Ship the product to the customer
12	Update the MAPICS records, complete the order

two constraint relations as shown in Figure 5.15. This is a conflict. In addition, we could figure out that "*manual operations*" exist in "*12 steps*", "*MAPICS (ERP)*" and "*manually converting electronic reports into MS Office (.doc and .xls formats)"*, by following the object "*including*". Thus, based on the ROM diagram, we are not only able to identify conflicts, but also able to figure out where the conflicts are originated from. In such a manner, proper solutions can be proposed to resolve the conflicts. By following the same pattern and the rules, several significant conflicts have been identified [3] as illustrated in Table 5.14 from Figure 5.14.

According to the EBD, before starting to resolve any conflict, we should analyze them first. The principle is to find out the dependencies among them as one conflict may be resulted from others. Two rules should be followed in resolving conflicts: (1) resolve the conflict from the natural environment first, followed by those from the built environment, with the conflicts from the human environment always being resolved last; (2) resolve the root conflict first. As such, handling a root conflict may eliminate other dependent conflicts. In this case study, any conflict resulted from human operations (conflicts 1, 2, and 3 for instance) are considered as the least significant ones, since a proper solution to conflict 6 may eliminate them. Figure 5.16 provides the proper answer to

[3] The conflicts are manually identified in this case study. However, ROM diagrams are able to be generated semi-automatically by a software called ROMA in the Design Lab at Concordia University. Conflict identification is to be implemented in the ROMA.

Table 5.12: Features of the current enterprise applications.

Applications		Features
MAPICS	Pro	reliable, powerful, modularized, electronic reports, supports a script language
	Con	command based, no GUI, manual operation only, too expensive to upgrade and no guarantee of correct data transferring, difficult to cooperate with other applications, documents cannot be read by other applications directly
AutoCAD	Pro	preview of drawings
	Con	no preview for odd version drawings, naming chaos of drawings, duplicated drawings, no batch printing function
MS Office	Pro	widely used for business documents
	Con	N/A

handle conflict 6.

By providing those application operators, employees can use their favorite application to get the information they are permitted to access. By refining these automated operations, conflict 5 and 9 can also be handled. For conflict 7, it is actually a part of the solution for conflict 6. Since the MAPICS supports a scrip language, with some small scale programming to refine the MAPICS' functionalities, the data in the ERP system's database could be retrieved to the shared database. Furthermore, through the ERP operator, the MAPICS can be manipulated, which is not possible before this solution. By using the two databases, one (the MAPICS' database, not directly accessible for other applications) can serve as a backup database, which enhances the robustness of the EAI solution in case of emergency. In order to resolve conflict 4, a segment of code was written using VBA, ActiveX, AutoCAD script and AutoHotkey (B. Chen, 2007). The code can automatically open the earlier version drawings that are without preview function by AutoCAD 2008, and save them as new versions that can be previewed. For each generated solution, it was put back to the ROM diagram again, and the three activities are recursively applied until no more unacceptable conflict exits. These recursive processes reflect the essence of the EBD – recursive logic (Zeng, 2002; Zeng & Cheng, 1991). After several iterations, the final solution was generated, which was

Table 5.13: Lifecycle analysis of the design problem.

Event	Natural	Built	Human
Design (Designer)	N/A	MAPICS (ERP system), difficult to cooperate with other applications, expensive to upgrade and no guarantee of data transferring correctly , MS Office, AutoCAD, no batch print function for AutoCAD	fully-automated, applications integration, smooth business processes
Manufacture (Programmer)	N/A	electronic reports cannot be read by other applications, only AutoCAD drawing after version 2000 can be previewed, budget for $10,000, MAPICS supports a scrip language, its own database, modularized, no interface, AutoCAD drawings with naming chaos and duplications	a sharing database, development tools
Use (Employee)	N/A	MAPICS, MS Office, AutoCAD, the company	12-step business process, user-friendly interfaces, not subject to human errors, emergency handling, data integrity guarantee, release employee from tedious from unnecessary manual operations
Maintenance (Technician)	N/A	the company	installation, deployment, add new modules/applications, emergency handling

implemented in the company. Figure 5.17 shows the functional graphic user interface for the final EAI solution.

5.2.6 Evaluation

In the real world, many enterprises are forced to upgrade their legacy applications/solutions for better business flow. However, it does not necessarily mean that every company has to give away its legacy applications for a major or total upgrade. For this case study, the final solution costed the company less than $10,000 (B. Chen, 2007). With the final EAI solution, the life of the legacy

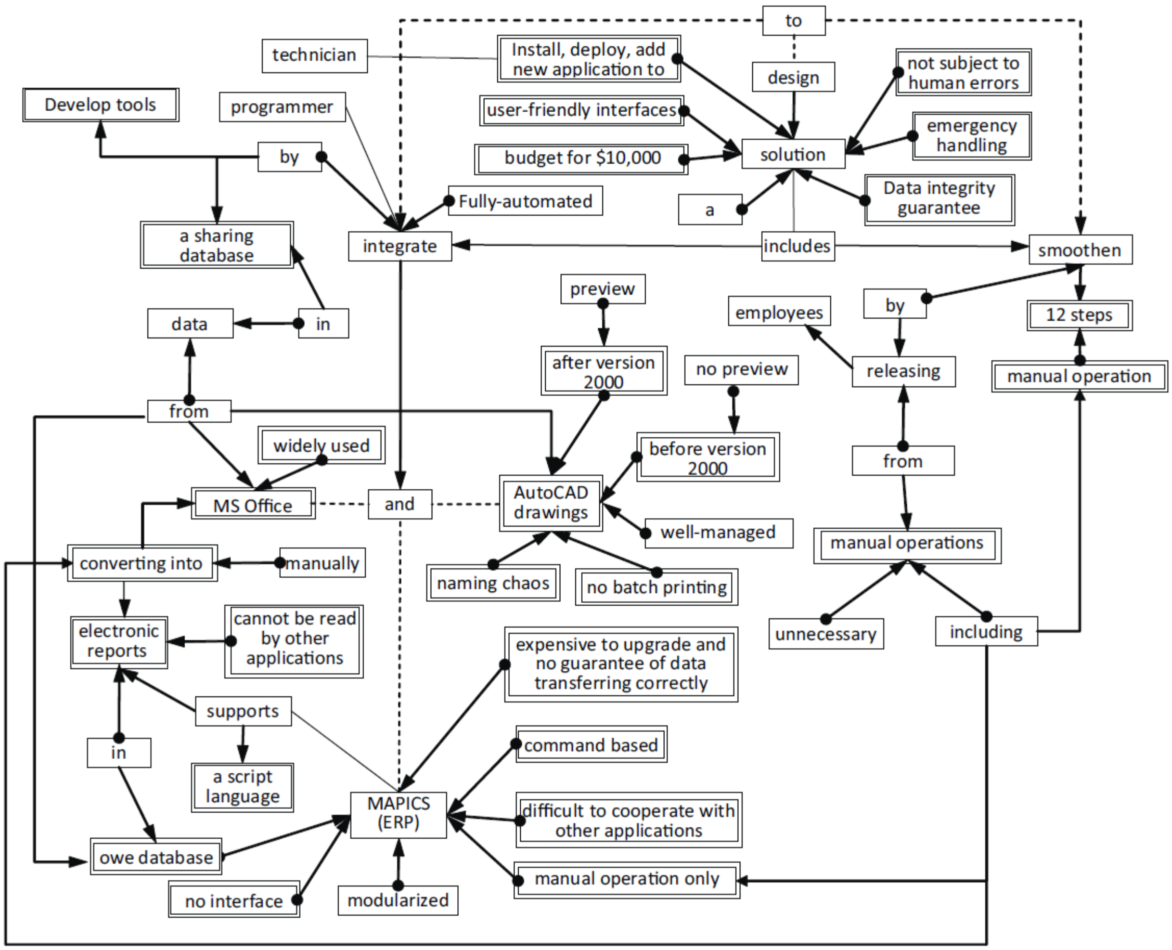

Figure 5.14: The most updated ROM diagram after question asking.

applications was extended. The business processes were improved significantly, and employees were much more content to work with it. Compared to upgrading (see Figure 5.10) which would cost the company at least $380,000 (Aberden Group, 2007) and would not be compatible with some of the legacy applications, the customized EAI solution not only satisfied the company in functionality without any side affects, but also provided a surprisingly huge saving – 97% of the cost for upgrading. Furthermore, since the design process and source code are available, the EAI solution could be well maintained and extended. Its configurability, extensibility and reusability indicate more potential savings and benefits for the company. In addition, the case study validated the effectiveness of the EBD approach and the proposed framework.

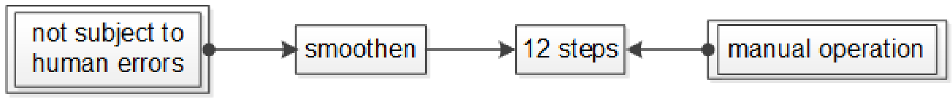

Figure 5.15: An example conflict.

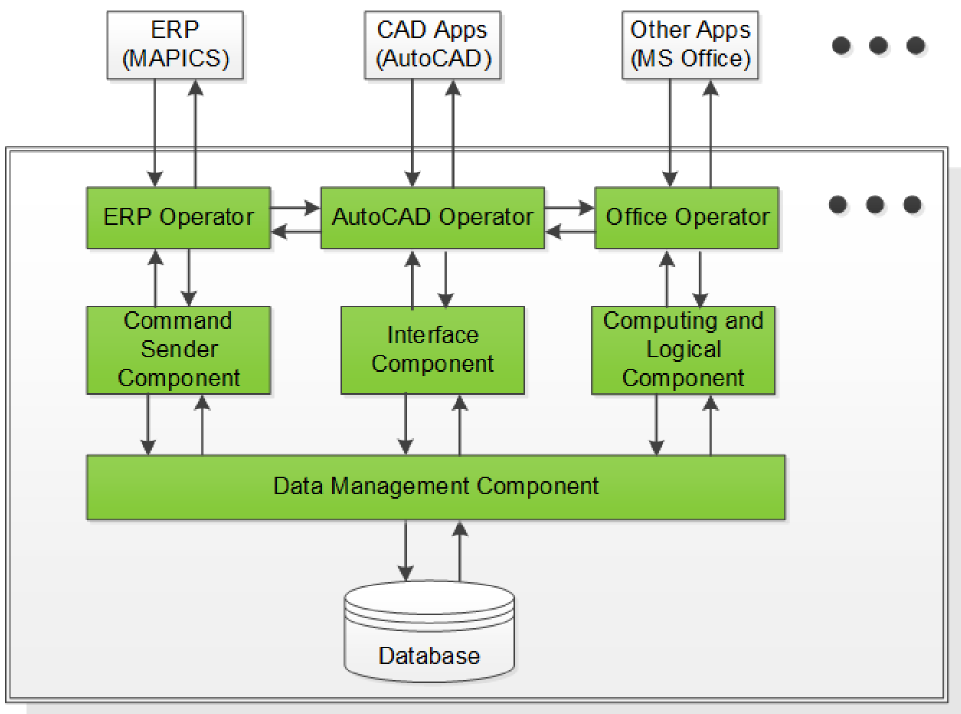

Figure 5.16: A database centered structure for applications integration (B. Chen, 2007).

Table 5.14: Conflicts identified from the most updated ROM diagram.

#	Conflicts	
1	eliminate unnecessary human operations	many human operations exist
2	not subject to human error	many human operations exist
3	fully-automated solution	many human operations exist
4	preview for drawings after version 2000	drawings before version 2000 exist
5	MS Office is widely used	electronic reports cannot be read by other applications
6	a sharing database	data from three applications
7	user-friendly interfaces	no interface
8	too many drawings are naming chaos and duplicated	get right drawings data from the sharing database
9	no batch print function	a desired function
10	emergency handling and data integrity guarantee	a sharing database

5.2.7 Conclusion

During the last few decades, EAI applications have become a very important issue for many enterprises. Many methods and technologies have been developed for EAI problems. In this case study, the Environment Based Design (EBD) methodology is employed to resolve EAI problems from design point of view. With the support of Recursive Object Model (ROM), it becomes logical and systematic to identify and clarify the requirements for the EAI problems. Based on that, a general framework for EAI problems is proposed. A case study from a SME (small and medium enterprise) is also presented. The EAI solution is used to demonstrate how a functional, cost-effective and efficient solution can be generated to smoothen the entire business processes within the company. Different from other methods, the EBD enables an EAI solution designer to identify the customer requirements, and to clearly understand how each given solution affects the whole product in its lifecycle at design stage. Therefore, the imperfect and defective solutions can be identified and eliminated at a very early stage.

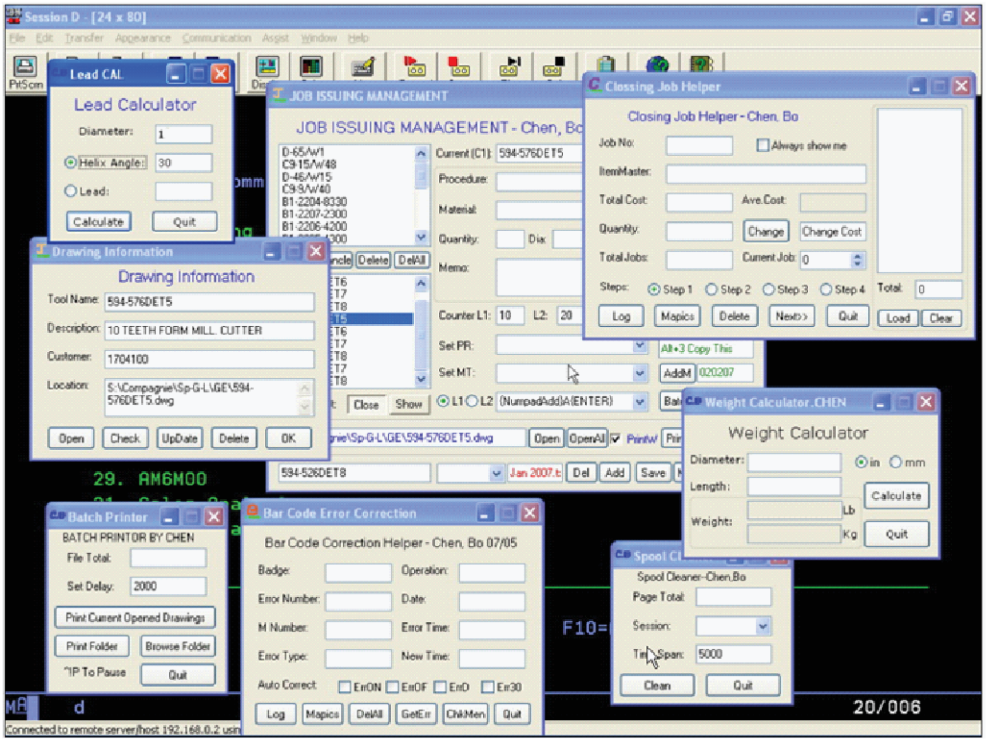

Figure 5.17: The user-friendly interfaces of the final EAI product (B. Chen, 2007).

5.3 Hardware Design Application - Medical Devices Design[4]

The demands of designing safe and effective medical devices have significantly increased for the past decades. For example, Long (2008) expressed a demand of improving current orthopedic medical devices by illustrating and discussing the uses, general properties, and limitations of orthopedic biomaterials. The emergence of fraudulent devices drove the need for regulations (Rados, 2006). Countries all over the world have established their laws and regulations to systematically manage the medical devices in their markets. In United States, for example, to assure the safety and effectiveness of medical devices in its market, the FDA (Food and Drug Administration) has established three regulatory classes based on the level of control: Class I General Controls (with or without exemptions), Class II General Controls and Special Controls (with or without exemptions), and Class III General Controls and Premarket Approval. For Class I and some Class II devices, simple controls will suffice for FDA clearance. Class III medical devices are subject to quality system

[4]The content of this section has been published as a journal paper in (Tan, Zeng, & Montazami, 2011)

requirements and stringent adverse event reporting and post-market surveillance (Pisano & Mantus, 2004). For companies that produce Class III medical devices, a premarket approval (PMA) will be required before the devices can be marketed. This is because the risk to the user or patient determines that a mass of trials have to be done before approval (Schuh, 2008). All device manufacturing facilities are expected to be inspected every two years.

Although governments are regulating the medical devices to ensure safety, it is estimated that 44,000 to 98,000 people die in hospital each year because of preventable medical errors, according to a report released from the Institute of Medicine (Kohn et al., 1999). This is more than the number of people who die annually from motor vehicle accidents, breast cancer, or AIDS (M. Chen et al., 2005). It makes hospital-based errors alone the eighth leading cause of death in the United States Altman, Clancy, and Blendon (2004). Among different preventable medical errors, a large portion is related to their misuse (M. Chen et al., 2005). Rousselle and Wicks (2008) presented the importance of customizing every aspect of the preparation process to the type of device and the study endpoints for pathologist, in order to avoid any error that may result in irreparable loss. According to (Kaye & Crowley, 2000), user-related errors can be divided into user-interface issue, user-environment issue, and user issue. Those user-related errors are usually a result of the ignorance of human factors in the design of medical devices (Z. Y. Chen, 2006). Hence, human factors are significant aspects that designers should take in consideration to improve the safety and performance of medical devices.

Human factors engineering (HFE) is the science and the methods used to make devices easier and safer to use (Food and Drug Administration, 2003). HFE improves the usability, performance, reliability, and user satisfaction of a product. Meanwhile, it reduces operational errors, training expense, and operator stress. It is often interchanged with the term “ergonomics”. The inclusion of human factors in medical devices design will definitely help the designer consider the users’ characteristics and hospital environment settings in a more effective manner (M. Chen et al., 2005). The consideration of such factors may introduce massive overhead in the development of medical devices, but it is significant and beneficial. Extensive research on HFE in the field of medical device design has been conducted (Fairbanks & Wears, 2008; Ginsburg, 2005; Gosbee, 2002; Lin, Vicente, & Doyle, 2001; Malhotra, Laxmisan, Keselman, Zhang, & Patel, 2005; Martin, Norris, Murphy, & Crowe, 2008). Lin et al. (2001) highlighted the benefits of HFE by the comparison of two simulations, one with HFE while another not. The results supported the idea that HEF improved patient safety in clinical setting. Gosbee (2002) presented a case study with vulnerabilities of human factors design and its analyses to illustrate the crucial role of HFE in patient safety. Ginsburg (2005) conducted a human factors evaluation to inform hospital procurement decision-making in selecting a general-purpose infusion pump. The author initialized a human-factor heuristic assessment of pumps according to four sets of criteria, and followed by a task analysis from designers' and users' feedback to rate their usability. Then the Human Factors Engineer visited different clinical areas to get participants' rates of the pumps within preset scenarios and the usability error. Based on the usability rates and usability error, a better decision was made for hospital procurement. However, there were limitations for this study, no one pump won in every aspect, trade-offs must be made, and cost efficiency was not considered. This study was only for user-end assessment, not at the design phase. Malhotra et al. (2005) proposed a cognitive approach for medical devices design. By obtaining information related to medical errors and patient safety through investigations, the device design process could be customized and modified for better patient safety management. In this way, the end-production could be creative and successful in market competition. Kools, van de Wiel, Ruiter, and Kok (2006) proposed another cognitive method to contribute to the design of effective health education information. By using pictures, the end user could better understand the medical devices that were inherently less clear. Kools illustrated an intuitive and reasonable way to reduce the chance of potential misuse of medical devices. This supported the idea Berman (2004) presented. Fairbanks and Wears (2008) highlighted the role of design in medical devices form several of previous work. Technology, manufacturing, regulations and rules, human factors, those conditions come together to enable a medical device to be designed safe and reliable. Martin et al. (2008) gave a comprehensive review on HFE (ergonomics) by applicable methods in medical devices design.

This case study aims to use the environment-based design (EBD) approach to design a medical device by analyzing design requirements in terms of product environments. A brief introduction is given in the subsection two followed by a subsection describing a case study on a particular medical device design process, with human factors considered prior to the design stage based on the EBD model. A conclusion is addressed in subsection 4.

5.3.1 The Design Problem

Novatek International Inc. is a global leader in providing innovative, leading edge and user-friendly LIMS (Laboratory Information Management System software) and other solutions that target the pharmaceutical, biotech and other health-care industries. While collaborating with Novatek several years ago, the EBD was adopted for the design of a new product. The description of the product is given as follows:

"Design an automated system to rapidly read various commercially available lateral flow tests using image recognition technology. The system should be effective and cost-efficient. It is for laboratory research. The solution should include a software kit which is compatible with the Novatek LIMS."

5.3.2 Environment Analysis

From the design description, a ROM diagram is drawn as Figure 5.18. To better understand it, the ROM diagram is simplified, and the objects are ordered in a neat format as shown in Figure 5.19. It is clear that the purpose is "Design a system to read tests" in short (see the bolded lines in Figure 5.19. Furthermore, we can observe five critical environment components and relations: system, read, tests, kit and LIMS, as they are the most constrained objects. However, they are not the only environment components and relations. As previously described, the less obvious components can be found by object analysis. According to the rules of object analysis presented by (M. Wang & Zeng, 2009), we start to ask questions regarding the unclear constraints of the object "system": "What do you mean by effective and cost-efficient?", "What kind of laboratory?", "What do you mean by automated?", etc. Moving to the object "read" afterwards: "What is the image about?", "What do you mean by rapidly?". Update the diagram with the answer to each question, until every object is clearly defined.

The most updated and simplified ROM diagram for object analysis is shown in Figure 5.20. We can observe that, the environment components and relations, system, LFR, holder, software kit, and image, are different from the previous. This has resulted from decomposing one object or combining several objects into one. Actually, there are hidden environment components and relations that

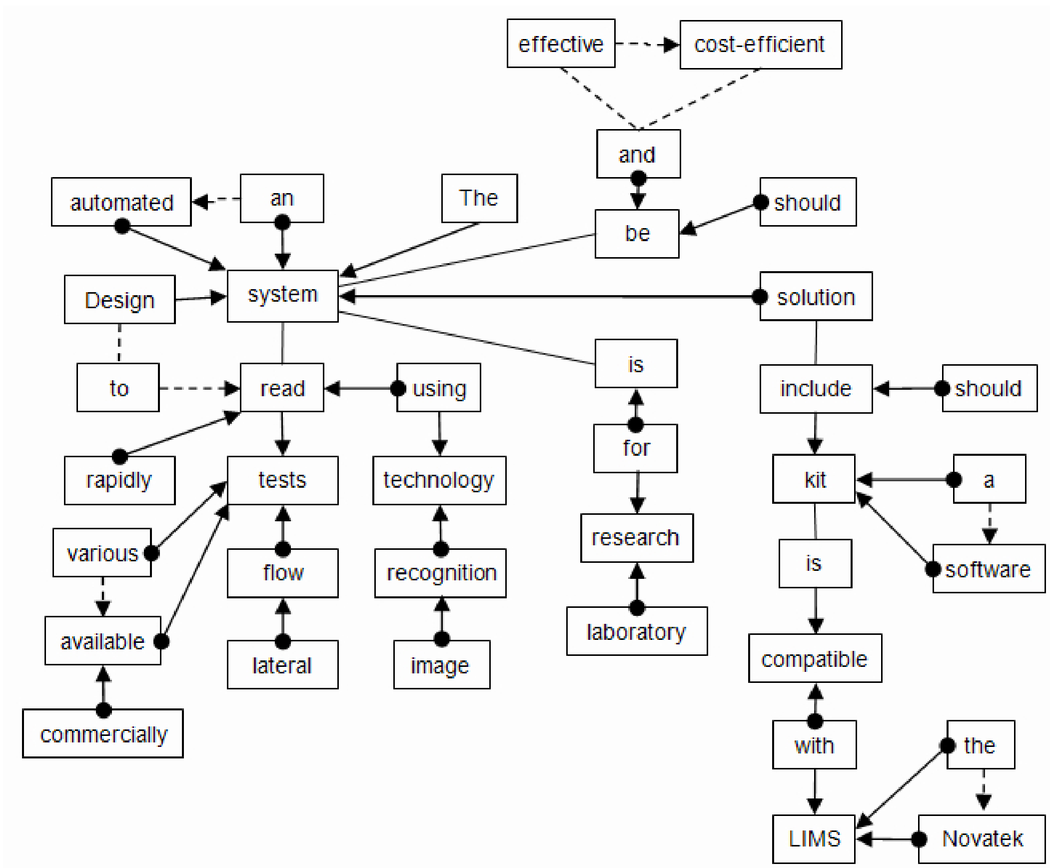

Figure 5.18: An initial ROM from the description.

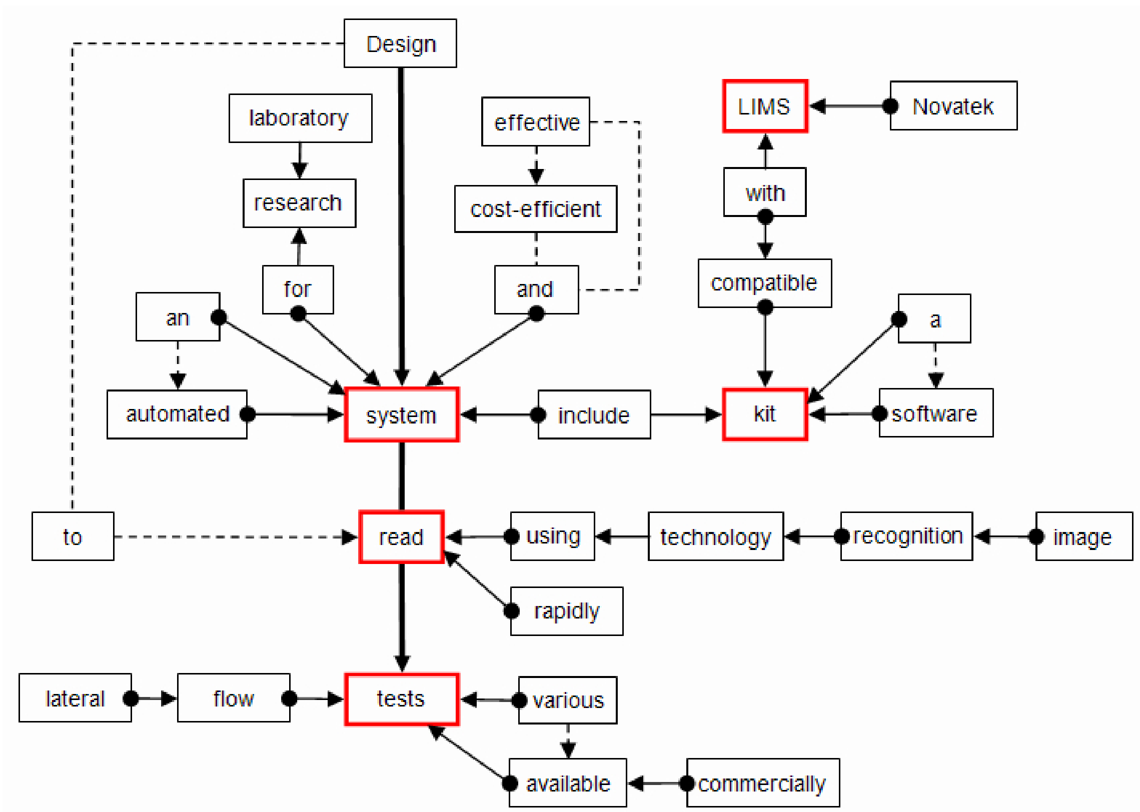

Figure 5.19: The simplified ROM diagram.

needed to be discovered. For example, the product is going to be launched in the US market and according to FDA's definition of a medical device, the product is a medical device indeed. In this case, FDA regulations should be considered as social laws applied to this design process. Among those, the 21 CFR Part 11 rules are viewed as the procedure for turning uncontrolled electronic data into controlled data that has an auditable paper trail (Pisano & Mantus, 2004). Therefore, auditable trail is a hidden required function for the product. This example highlights essential of the roadmap for the design process.

According to the roadmap mentioned in Chapter A, the life cycle for this product is divided into five kinds of events; they are design, manufacture, sales, use, and maintenance. For each event, the requirements are further classified into nature, human, and built environments. The details are show in Table 5.15. And the ROM diagram can be further updated as shown in Figure 5.21.

Table 5.15: A tables of brief requirements classified in environment.

Event	Natural	Built	Human
Design (Designer)	N/A	FDA regulations, modularization half-year development time, a development team, Novatek LIMS	image recognition, compatible with various commercially available lateral flow device types
Manufacture (Worker)	N/A	budgeted	[size/shape/color/material]*, confined box, software kit is compatible with Novatek LIMS
Sales (Salesman)	N/A	existing similar products in the market	1/3 of average retail price
Use (User)	lines are undetectable (faded away) after long time, lateral flow tests are accurate within 4 to 20 minutes	laboratory, LIMS	accuracy guarantee, change devices, automatic verification, specifications, error- detectable, user guidance, exception-handling guidance, error- detectable, capable of analyzing predefined number of samples, user-friendly interface, definable user access right, independent audit trail, extendibility, low power consumption, capable of detecting errors automatically
Maintenance (Technician)	N/A	warranty	software update automatically, replace the damaged module

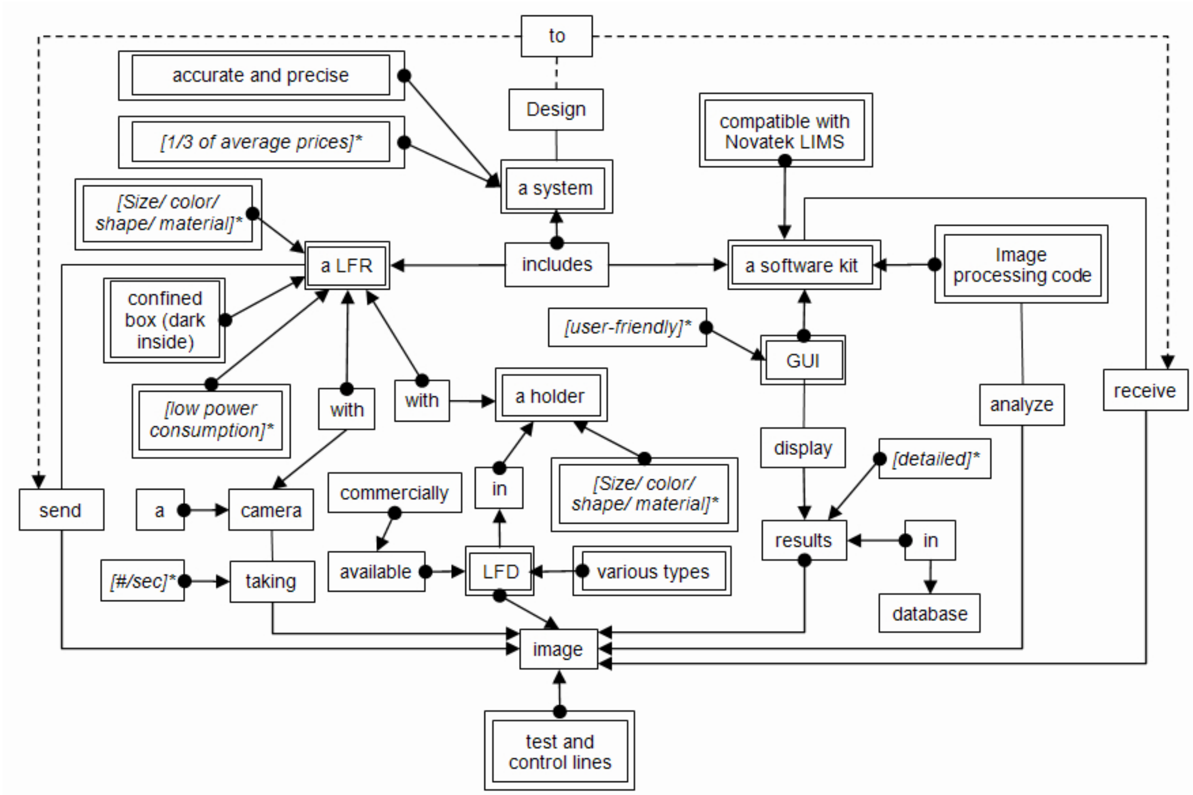

Figure 5.20: The updated ROM diagram after object analysis. LFR: lateral flow reader; LFD: lateral flow device; GUI: graphic user interface. ([ ]*: Due to intellectual property protection, only conceptual descriptions are given.)

5.3.3 Conflict Identification and Solution Generation

As can be observed from Figure 5.21, the major environment components and relations are system, a LFR, a software kit, image, LFD, holder, results, confined box, module and GUI. And, there are six critical conflicts as listed in Table 5.16. Conflict 1 is a conflict resulted from the most basic level (see Table 5.15), and it is the most critical conflict for the basic functions that should be solved first. We can either solve it by reading the test result within 20 minutes after a test or by another method that is not limited by the test time. Finally, [line-restore technology]* and [sophistic image processing code]* are adopted to handle the conflict. Since conflict 1 is the root of conflict 2, the solution to conflict 1 will eliminate conflict 2 as well. It introduces an increase of cost, but it is a must. For conflict 3, we can put an illuminant inside. But this illuminant device increases the cost

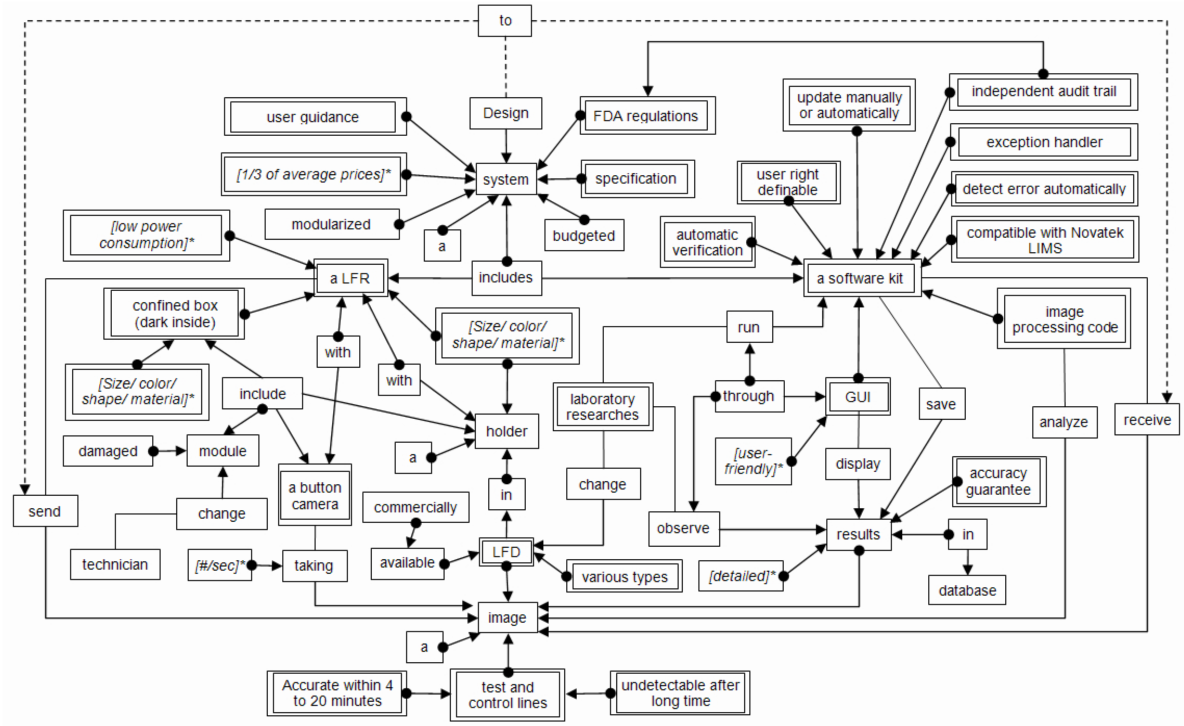

Figure 5.21: A further updated ROM diagram.

and consumes additional power, which in fact introduces two additional foreseeable conflicts which are unacceptable. Finally, a [smart solution]*is adopted for this conflict without introducing any new conflicts at all. For conflict 4, an adjustable holder was proposed. The solution is designed for various LFD types from several manufacturers. By refining the code and designing a small drawer, conflicts 5 and 6 are handled. For the LFR, a USB cable can serve as both a power supply and a data transmission channel when connected to a computer. So far, the most critical conflicts are handled without bringing any undesired problem. We then repeat all the steps and add the solutions back to the ROM diagram, until there are no more unacceptable conflicts.

The product to be designed is a medical device, which requires higher level of "safety and effectiveness" by FDA. As the LFR itself is not harmful for any living beings, much attention has been put in effectiveness and efficiency of the system, in other word software improvements. Based on an updated ROM diagram, we can clearly figure out what kinds of improvements are needed and how they improve product quality. As can be seen in the most updated ROM (Figure 5.21), many efforts were made to ensure that interface issue, user-environment issue, and user issue are

Table 5.16: Conflicts identified from Figure 5.21.

#	Conflicts	
1	Analysis the image with lines	The lines are undetectable
2	Accurate within 4 to 20 minutes	Accurate and prices guarantee
3	With a camera taking picture	Confined box (dark inside)
4	A holder	various LFD types
5	An image processing code	Image of various LFD types
6	Researcher change LFD	Confined box

thoroughly considered. With continuous communication with the company, the manufacture agent and customers, the EBD was recursively applied in the design process to make it better. After four prototypes, the product was finally released to the worldwide market. The design process in this case study does not dig too deep into the details due to intellectual property protection. However, it includes HMF as we can see from the Table 2. The effectiveness and efficiency is obvious. As a matter of fact, the product was endowed several new features at its release (see Table 5.17), some of them were better than expected.

Table 5.17: Features of the final products.

#	Feature
1	1/8 - 1/10 of the marketing price of existing similar devices
2	Lowest power consumption
3	Automatic verification
4	Capable of detecting errors automatically
5	Capable of analyzing predefined number of samples
6	Eliminates or compliment/expedite manual verification
7	User friendly GUI
8	Guaranteed accuracy
9	FDA's 21 CFR part 11 rules compliant
10	Definable user access rights
11	Extensive independent audit trail

5.3.4 Discussion

As many people suffer from failures in medical applications and those failures are related to human factors, it is suggested that a medical device designer should be equipped with a design methodology to conduct all-around requirement analysis of a medical device. Environment-based design is such methodology that enables a designer to define all design requirements in terms of the environment where the device is expected to function, which includes natural, human, and built environments. Based on the EBD, a designer is not only able to clearly understand described design requirements from customers, but also able to discover hidden requirements from other aspects. The case study shows how the EBD is applied to a medical device design problem, with considering human factors at its design stage. And it indicates the effectiveness and efficiency of the method. The EBD is not limited for medical devices design. It is able to provide a comprehensive analysis and a satisfactory solution for every design problem.

Chapter 6

Conclusion

6.1 Research Achievements

There is an evident demand for evaluating designer's perception and performance in conceptual design phase. The overall objective of this thesis is to understand the role of perception in engineering design, and identify the basic factors involved in evaluating a designer's performance and perception based on his/her solution iterations in a design process, especially in the conceptual phase. The work has been carried out with three focused sub-topics: (1) to develop a method to quantify designer's performance at the conceptual design phase; (2) to propose a theoretic model for evaluation of designer's perception at the conceptual phase; (3) to conduct experimental study to validate the proposed hypothesis.

As a result, a theoretical model was derived from the inverse U curve and the stress formula to represent the roles of perception in a design process. In this model, workload, skills, knowledge, and affect were used as major factors to quantify a designer's performance. In addition, methods were proposed to evaluate a designer's perception and performance in conceptual design phases. The model and the methods have been applied as tools to evaluate one's performance and perception ability, by framing design activities using Environment-Based Design methodology. The model not only serves well as a stage-based assessment tool for conceptual design solutions, but also implies a foundation to improve one's performance for engineering design. The proposed model has been validated by the experimental study. From the study, a significant positive correlation between perception and performance has been found. Furthermore, the results indicate that the factor "skill" is more favorable to improve designer's performance through correct perception in a timely manner.

6.2 Contributions

The contributions of this research are two folds: theoretical contributions and engineering design applications. The theoretical contributions are outlined as follows:

(1). A theoretical model about the role of perception in engineering design (derived from the inverse U curve and stress formula);

(2). A method to evaluate designer's perception in conceptual design;

(3). A method to evaluate designer's performance;

(4). Statistical validation of positive correlation between designer's perception and performance.

While, the engineering design applications include the following:

(1). Reverse design approach based on EBD, which has been applied to an Engineering Design Education program as a foundation;

(2). Software design using EBD;

(3). Medical device design using EBD.

Those engineering applications have, on one hand, shown the effectiveness of the Environment-Based Design methodology. On the other hand, they reflect the role of perception in design. Prioritizing and question asking are actually involved in our daily life to work and to live. In other words, design is everywhere and every kind of problem can be seen as a design problem to solve.

6.3 Future Work

Future work will focus on cognitive evidence. It is expected to use EEG (electroencephalogram), HRV (Heart rate variability) and eye-tracking devices to record a designer's physiological signals in a design progress to measure his/her stress, and then integrate valuable knowledge into the proposed model. From this perspective, the “reflecting” activity can be further decoupled into more primitive ones according to a designer’s brain activities. We can thus be able to apply a cognitive evidence-based video segmentation method to data analysis, to have a better understanding on designer’s “real” perceptual activities and its relation to designer’s performance. In addition, more subjects and more experimental results are expected in the future work.

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Journal Papers

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Book Chapter

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Appendix A

The EBD Methodology

Apart from traditional design methodologies, the EBD methodology (Zeng, 2004, 2011; Zeng & Gu, 2001) was logically derived from the axiomatic theory of design modeling (Zeng, 2002), which was founded on the recursive logic of design (Zeng & Cheng, 1991). The idea behind the EBD is that the design problem implied in the development of a product system is composed of three parts: the environment in which the designed product is expected to work, the requirements on product structure, and the requirements on performance of the designed product. The requirements on product structure and performance are related to the product environment. In addition, the product environment includes three major environments: natural, built, and human, shown in Figure A.1. The EBD includes three main steps: Environment Analysis, Conflict Identification, and Solution Generation. These three steps work together progressively and simultaneously to generate and refine the design specifications and design solutions.

The objective of environment analysis is to find out the key environment components, in which the product works, and the relationships between the environment components. From the environment implied in the design problem described by the customer(s), a designer will introduce extra environment components that are relevant to the design problem at hands. The results from this analysis constitute an environment system. One of the key methods for environment analysis is linguistic analysis (Z. Chen et al., 2007). The Recursive Object Model (ROM) was proposed by Zeng (2008) to conduct this work. The ROM includes two types of objects, which are object and compound object, and three kinds of relations between any two objects: connection, constraint, and

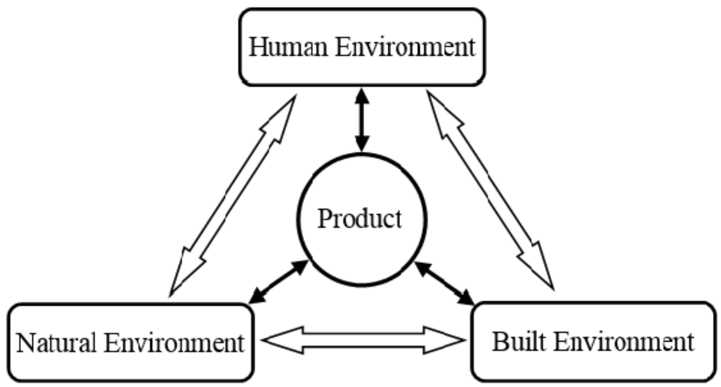


Figure A.1: Three major environments for a product working in (M. Chen et al., 2005).

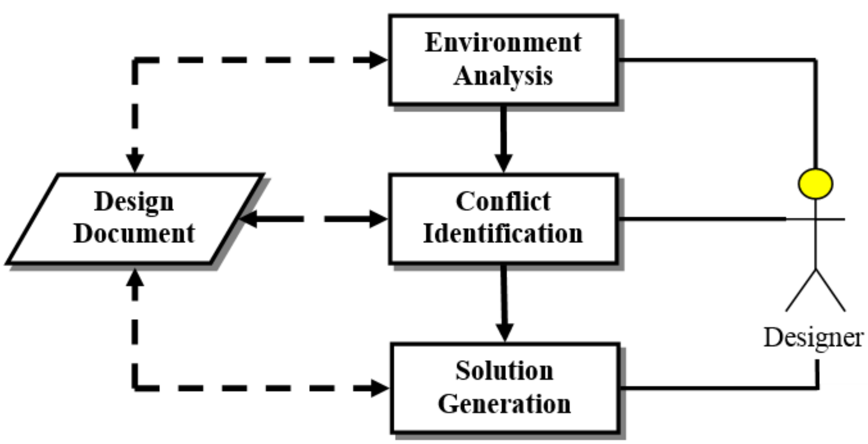
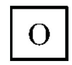
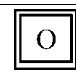
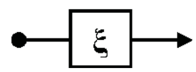
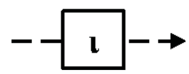
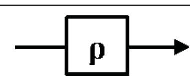


Figure A.2: Environment-Based Design: process flow (Zeng, 2011).

Table A.1: Elements defined for the ROM (Zeng, 2008).

Type		Graphic Representation	Description
Object	Object		Everything in the universe is an object
	Compound Object		It is an object that includes at least two objects in it
Relation	Constraint Relation		It is a descriptive, limiting, or particularizing relation of one object to another
	Connection		It is to connect two objects that do not constrain each other
	Predicate Relation		It describes an act of an object on another or that describes the states of an object

predicate (as shown in Table A.1).

While a ROM diagram is generated, some questions are asked to make every object in the ROM diagram clear. M. Wang and Zeng (2009) gave the rules on question asking to conduct a comprehensive environment analysis. General questions are asked by following the question templates in shown in Figure A.3.

In order to verify the completeness of the extracted environment components and their relations, a roadmap was proposed as guidance for requirements modeling (Z. Y. Chen & Zeng, 2006). In this roadmap (see Figure A.4), requirements (structural or performance) were categorized by two criteria in terms of different partitions of product environment. One criterion classifies the product requirements by partitioning product environment in terms of product lifecycle, and the other one classifies them by partitioning the product environment into eight levels: Natural laws and rules, social laws and regulations, technical limitations, cost, time and human resources, basic functions, extended functions, exception control, and human-machine interface. The eight levels are in fact decomposed from the natural, built, and human environments for better extraction of the environment components. The lowest level comes from the nature environment; three levels in the middle represent built environment; the rest four are from human environments. Following the pattern of

	Conditions	Question
T1	For a concrete, proper, or abstract noun N	What is N?
T2	For a noun naming a quantity Q of an object N, such as height, width, length, capacity, and level	How many / much / long / big / … is the Q of N?
T3	For a verb V	How to V? Or Why V?
T4	For a modifier M of a verb V	Why V M?
T5	For an adjective or an adverb A	What do you mean by A?
T6	For a relation R that misses related objects	What (who) R (the given object)? Or (the given object) R what (whom)?

(c) Question template for object analysis

Figure A.3: Question templates for EBD (M. Wang & Zeng, 2009).

such environment analysis, conflicts are then identified among the relations between environment components (Zeng & Chen, 2005). There are several rules to follow for conflict identifications (Yan & Zeng, 2011; Zeng, 2004, 2011):

Rule 1 If an object has multiple constraints, then potential conflict exists between any pair of constraining objects.

Rule 2 If an object has multiple predicate relations from/to other objects, then potential conflict exists between a pair of those predicate relations.

Rule 3 If an object is constrained by another object, then the relation is inherited by its sub-objects, e.g., an object O_1 is constrained by another object O_2, and O_1 has two component O_{11} and O_{12}. O_{11} and O_{12} are considered being constrained by O_2.

Figure A.5 shows three forms for a possible conflict existing in a ROM diagram. `A`, `B1`, `B2`, `R1` and `R2` are existing objects (relations are seen as objects as well (Zeng, 2002)). `C` stands for a possible conflict. `A` is called the resource object, `B1` and `B2` or `R1` and `R2` are two competing objects (Yan & Zeng, 2011). Specifically, Fig. A.5.(a) shows a possible conflict between two

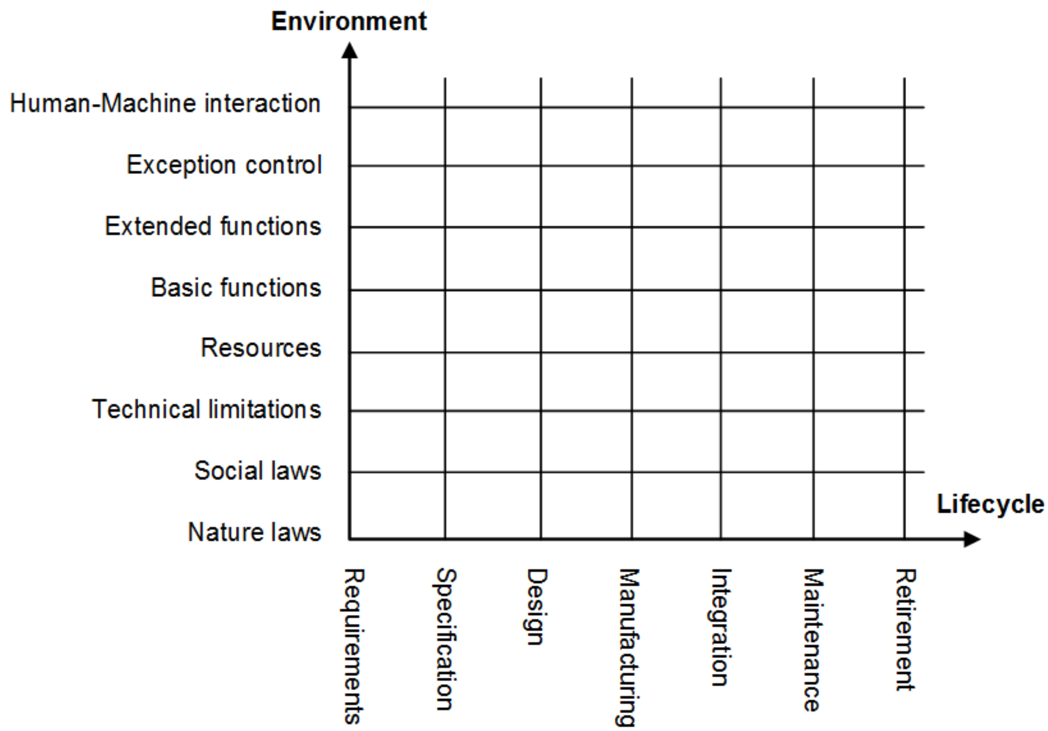


Figure A.4: A roadmap for design requirements classification in terms of product life cycle and environment hierarchy (Z. Y. Chen & Zeng, 2006).

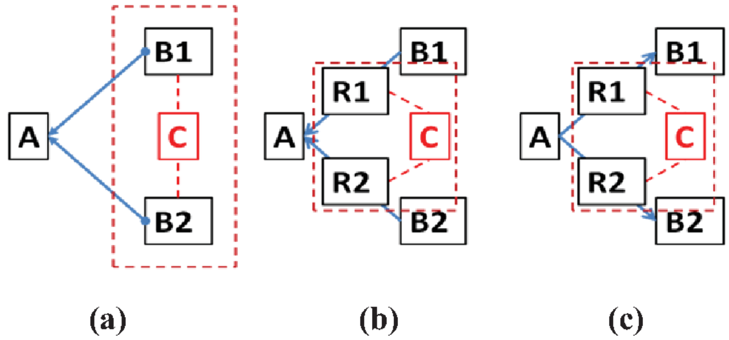


Figure A.5: Three forms of an existing conflict in a ROM diagram (Yan & Zeng, 2011; Zeng, 2004, 2011).

constraints – resulted from conflicting constraint relations. Figs. A.5.(b) and (c) show two other forms – resulted from predicate relations. Please notice the different direction of predicate relations in Figures A.5.(b) and (c). How to apply them to practice is shown in the case study later.

At the third stage of EBD, a set of key environment conflicts are chosen to be resolved by generating some design solutions. This process continues until no more unacceptable conflicts exist.

Appendix B

Benchmark and Evaluation

Since design is a recursive process, during which design problem, design solutions, and design knowledge evolves simultaneously, the contents will be presented based on iterations. The iteration(phase)-based evaluation model start with the design problem statement while take the product life-cycle in consideration. In this chapter, we illustrated only one iteration for subject 3 in details to show the evaluation process.

B.1 Iteration 1

B.1.1 Environment Analysis

Step 1. Draw the ROM diagram for the design problem description

First of all, a ROM diagram is generated with the given initial statement – "Design a house which can fly easily from one place to another.". Apparently, a word "place" is omitted at the end of sentence. With the word add back in, we have a ROM as Figure B.1. It shows the components included in the initial product-environment system and the relations between the components.

Step 2. Identify Product-Environment System (PES)

The second step of Environment Analysis is to identify Product-Environment System (PES) from the ROM diagram. According to the rules introduced in Chapter A, the product in this case

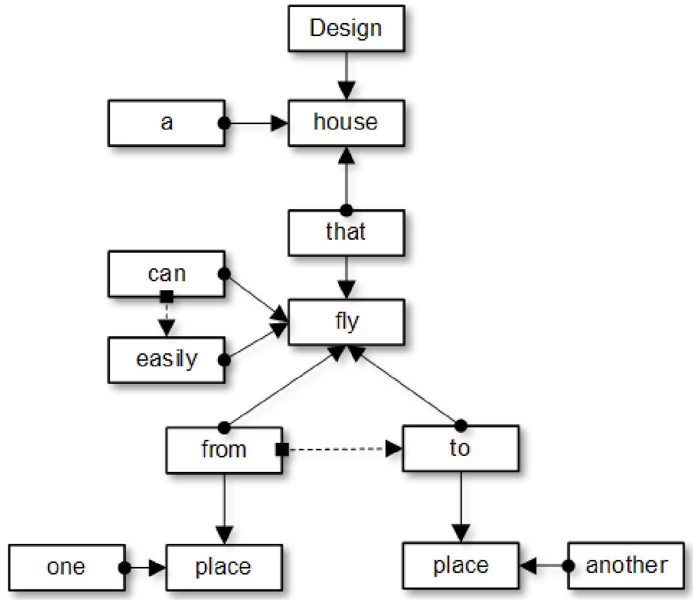


Figure B.1: ROM diagram representation of the problem statement.

is "house". Environment components are two "place", modified by "one" and "another" respectively. An interaction between the product and its environment is "fly", which is modified by "can", "easily", and "from to". Mathematically, the PES can be represented as Equation 6 shows.

$$
\begin{aligned}
S &= a * house \\
E_1 &= one * place \\
E_2 &= another * place \\
I_1 &= (can \wedge easily \wedge from \wedge (E_1 \bigotimes E_1)) * fly) \\
I_2 &= (can \wedge easily \wedge to \wedge (E_2 \bigotimes E_2)) * fly)
\end{aligned}
\tag{6}
$$

Step 3. Collect information about the Product-Environment System (PES)

Based on the identified Product-Environment System, more information is usually needed to develop the necessary understanding of the environment in order to deliver a product that can serve its purpose in the environment. The most effective manner to collect the right information is to ask the right questions by following rules listed in previous chapter and (Zeng, 2015).

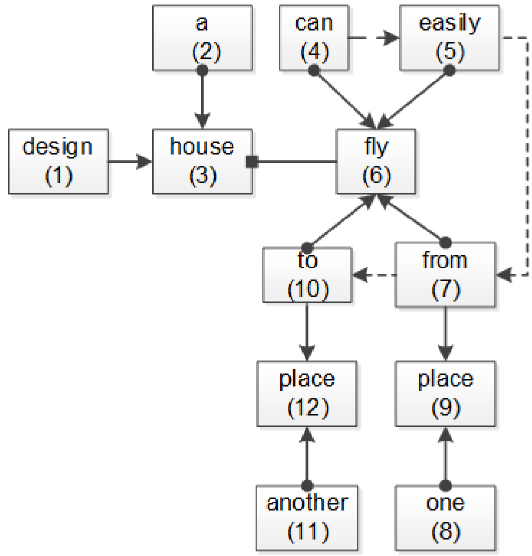


Figure B.2: Coding of the ROM objects.

(1). Rank ROM objects

The purpose of ranking ROM objects is to determine the order of questions. It consists of the three steps below.

(a) Code the objects in the ROM diagram, as shown in Figure B.2.

(b) Construct the ROM matrix, as shown in Table B.1.

Table B.1: Matrix for the coded ROM in Figure B.2

object	1	2	3	4	5	6	7	8	9	10	11	12
1			2									
2			3			1						
3	2					3						
4						3						
5												
6			1									
7						3			2			
8									3			
9							2					
10						3						2
11												3
12										2		

where, the value for each matrix element represents different relations:

$$r_{ij} = \begin{cases} 1 & subject-verbrelation \\ 2 & verb-objectrelation \\ 3 & constrainingrelation \\ 0 & Others \end{cases} \quad (7)$$

(c) Rank the ROM objects according to constraint and predicate relations on them, refer to B.2.

Table B.2: Number of constraint and predicate relations on an object.

Number of relations	5	3	2	1
object	6	3	9,12	1,7,10

(2). Define object list for questioning

The object list for questioning is defined in Table 13.3.

Table B.3: Objects to be questioned in their order.

Number of relations	5	3	2	1
Object	6	3	9,12	1,7,10
Questioning object list with orders	1,8,9,11,12,6,7,10,5,2			

(3). Generate generic questions

After defining the list of objects to be questioned, the generic questions in Table B.4 are obtained, based on extended question rules defined in (Zeng, 2015).

(4). Lifecycle analysis

A general lifecycle of an engineering design process spans many events, the major ones are requirements, conceptual design, manufacturing, transportation, integration, testing, sales, maintenance, and disposal. In this experimental study, conceptual design phase is the focus. Therefore, we will zoom in this single event to analyze its sub-lifecycle events. The two interactions (I_1 and I_2) in Step 2, in other words, the action “fly”, become the start point. The following is the benchmark for environment components in terms of the lifecycle analysis.

Table B.4: Question list with their order.

Order	Conditions	Questions
1	For a meta verb Vm that relates designer to a product system	Why to design a house to easily fly from one place to another?
2	For a noun object A constraining a noun object N	What are the places?
3	For a verb with its subject N1 and object N2	How does a house fly from one place to another place?
4	For a verb with its subject N1 and object N2	Why does a house fly from one place to another place?
5	For a verb with its subject N1 and object N2	When does a house fly from one place to another place?
6	For a verb with its subject N1 and object N2	Where does a house fly from one place to another place?
7	For a verb with its subject N1 and object N2	Who will fly the house from one place to another place?
8	For a verb modified by an adverb A with its subject N1 and object N2	What do you mean by easily fly from one place to another place?

Table B.5: Lifecycle analysis in term of the conceptual design phase.

Events	Nature	Build	Human
taking off	gravity, air resistance, different weather conditions, atmospheric corrosion, fly objects (birds, airplane), temperature profiles of air ($-30\,^{\circ}\mathrm{C}$ to $50\,^{\circ}\mathrm{C}$),	one place, SOP, regulations (FAR, JAR, etc), certifications, seats	operator, coordinator, passenger(s), exception warning system
cruise	gravity, air resistance, different weather conditions, atmospheric corrosion, fly objects (birds, airplane), temperature profiles of air (as low as $-56\,^{\circ}\mathrm{C}$, if in stratosphere)	seats, food, wash room, air conditioner, SOP, regulations (FAR, JAR, etc)	operator, coordinator, passenger(s), exception warning system
landing	gravity, air resistance, different weather conditions, atmospheric corrosion, fly objects (birds, airplane), temperature profiles of air ($-30\,^{\circ}\mathrm{C}$ to $50\,^{\circ}\mathrm{C}$),	another place, SOP, regulations (FAR, JAR, etc), certifications, seats	operator, coordinator, passenger(s), exception warning system

Based on the table, more environment components identified. They are available for being chosen as the desire requirements constraining the design solution, based on the designer's answer to the questions. For example, if a designer answers to the first question as, "needing an autonomous cargo warehouse". Then, some environment components, such as passenger is not applicable for his/her solution as requirements. Whereas, if a designer designs "a vacation house for family trips", then all the regulations and SOP are enforced by the "social laws" environment component (refer to A.4). To simplification, SOP, regulations (FAR, JAR, etc.) and certificates are not considered as requirements, as they are enforced more for manufacturing and sale events. In this way, 16 requirements were extracted in Table B.6, according to the analysis and the problem statement.

Table B.6: Question list with their order.

#	Requirements
1	considering gravity
2	considering flying objects
3	weather condition
4	temperature profile of air
5	taking off
6	air resistance
7	landing
8	define places
9	operator
10	passenger
11	level of details
12	cruise
13	exception warning system
14	make assumption(s)
15	write decision-making process
16	justification of design

B.1.2 Evaluation

The conceptual solution subject 3 delivered at the end of first phase (00:19:28s) is shown in the Figure B.3.

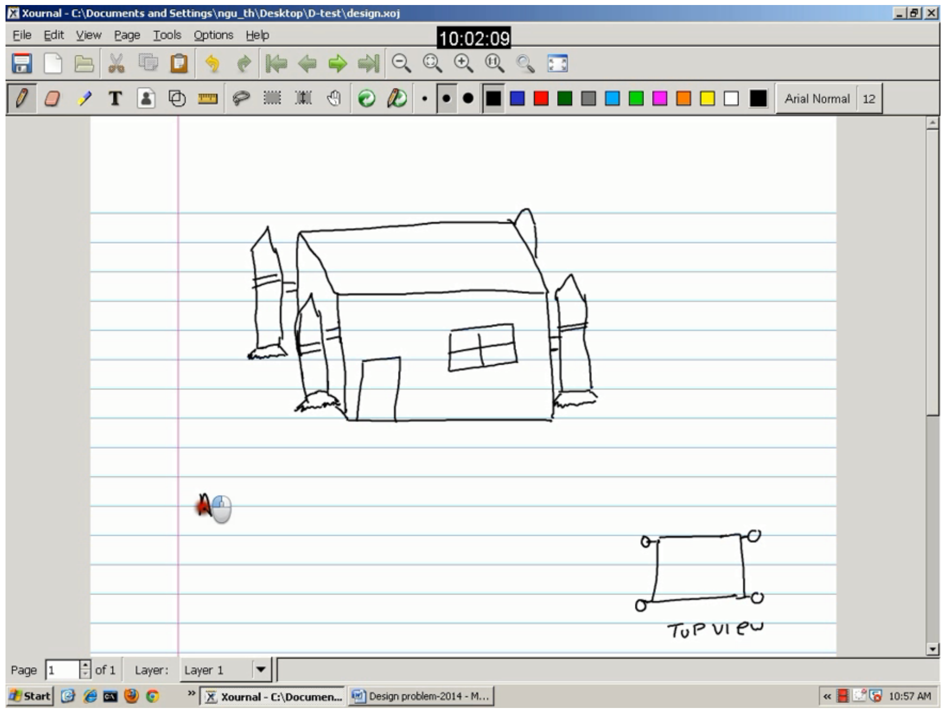


Figure B.3: The conceptual solution delivered by subject 3 at the end of the first phase identified.

Perception evaluation

At first design stage, according to the answer provided by the subject 3, he/she partially answered 3rd question. According to the Equation 4 defined in Chapter 3, his/her perception rate was calculated as

$$RC^1 = 2/3*(0+0+0.2+0+0+0+0)+1/3*((0+0+0.5+0+0+0+0)/7) \approx 0.1571 .$$

Performance evaluation

Subject 3 drafted the solution directly at in the first design phase, his/her solution includes: 4 rockets tided to four corners of the hours, door, windows, side view and top view, etc. According to the likelihood to satisfy the requirements in the Table B.6, his/her performance rate was calculated as

$$RP^1 = (1+0+1+0.5+1+0.5+1+0+0.5+0.5+0.5+1+0+0+0+0)/16 \approx 0.46 .$$

B.2 Iteration 2

With the solution/answers provided by the subject, the problem statement is updated in a new iteration. A new ROM diagram will be drawn based the new statements for environment analysis (the progress can be referred to the case studies presented in Chapter 5). The benchmark generation process and the evaluation processes proceed recursively, until the end of the final conceptual design phase.