Validation of Environment Based Design (EBD) through Applications of Design Chain Management and Quality Management System

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ABSTRACT

Validation of Environment Based Design (EBD) Methodology through Applications of Design Chain Management and Quality Management System

Xuan Sun

Environment Based Design (EBD) is a recursive design methodology including three interdependent design activities: environment analysis, conflict identification and solution generation. EBD gives detailed instruction and provides useful tools in each step, so designers can easily apply EBD in different fields. Also, EBD can give designers a sense of right direction by guiding them collect the necessary and sufficient information from existing environment and customer requirements, which help designers focus on the creative activities.

This thesis aims to validate the effectiveness of EBD methodology based on two case studies. One is the formalization of design chain management (DCM). A formal conceptual model for DCM is generated from its informal definition by applying EBD. This effort is different from other existing approaches to developing conceptual models in that the model is derived step by step from the natural language description of the DCM. The logical and interpretable formalization process of DCM shows EBD is an effective design methodology. In the second case, EBD is adopted to develop a Quality Management System (QMS) and generate a quality manual for an environment monitoring service. The challenge was that the content and structure of the final manual

were not clear to the customer. By taking this task as a design problem, EBD helps get the real customer requirements from a fuzzy description and develop the QMS by solving the root conflicts. This application of EBD shows the effectiveness of the EBD as a generic design methodology.

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Chapter 1 **Introduction**

1.1 Background and Motivation

All human activities can be roughly classified into two categories: to know the world and to change the world. While studies into the nature such as physics and chemistry attempts to know the world, studies in such fields as design and manufacture attempts to change the world (Zeng, 2004). Environment-Based Design (EBD) methodology is a recursive design methodology introduced by Dr. Zeng in 2004 (Zeng, 2004). EBD includes three interdependent design activities: environment analysis, conflict identification and solution generation, which have specific instructions and defined rules. EBD can give designers the right direction by analyzing the existing environment and customer requirements (Zeng, 2011). The validation of design methods can guide the development and evaluation of new design methods, which is important for the continuing advancement of both design theory and the professional practice of engineering (Frey and Dym, 2006). Therefore, the evaluation of a design methodology – EBD requires a validation.

1.2 Objective

The objective of this thesis is to validate the effectiveness of EBD as a generic design methodology. Effectiveness is defined as "extent to which planned activities are realized and planned results achieved" (ISO9000, 2005). In another word, effectiveness means 'doing the right thing' (Businessdictionary, 2011). The validation of EBD is conducted based on two applications. One is the formalization of Design Chain Management (DCM). A formal conceptual model of DCM is generated from its informal definition by applying EBD. This effort is different from other existing approaches to developing conceptual models in that the model is derived step by step from the natural language description of the DCM. The logical and interpretable formalization process of DCM shows EBD is an effective design methodology. In the second case, EBD is adopted to develop a Quality Management System (QMS) and generate a quality manual for an environment monitoring service. The challenge was that the content and structure of the final manual were not clear to the customer. By taking this task as a design problem, EBD helps get the real customer requirements from a fuzzy description and develop the QMS by solving the root conflicts. This application of EBD shows the effectiveness of the EBD as a generic design methodology.

1.3 Contribution

This thesis focuses on the validation and application of an effective design methodology - EBD. The main contributions of this thesis include:

(1) A conceptual model is proposed for design chain management development. Instead of traditional ways, this DCM conceptual model is derived step by step from the natural language description, where four different types of models – task centered model, process centered model, product centered model and performance centered model work together to resolve problems in the DCM process from different aspects. Also, the product centered model – Product Lifecycle Management (PLM) wheel model is generated based on the analysis of EBD. There are six parts implied in the PLM wheel model: product lifecycle, product data, standards, business processes, technology tools, and stakeholders. This wheel model classifies and summaries the

types of conflicts that may appear in the PLM, and supplies corresponding solutions for each type of conflicts.

(2) EBD is used to develop a quality management system and generate a quality manual for a monitoring service. The developed QMS uses computer program instead of some human operations, which can enhance quality and accuracy of data assurance, improving the efficiency of data quality assurance and avoiding human errors by relieving technologists of a heavy workload. The quality manual including correct sequence of monitoring activities and operation instructions helps construct the standard operation and ensure the effectiveness and efficiency of monitoring operation.

(3) In the QMS case study, direct graph and adjacency matrix are introduced as specific tools for representing dependency relations between conflicts and detecting root conflicts.

1.4 Thesis Organization

The rest of this thesis is organized as follows:

(1) Chapter 2 reviews related work in design methodologies, validation of design methodology, design chain management (DCM) models and quality management system (QMS) development;

(2) Chapter 3 introduces the theoretic foundation of Environment-Based Design (EBD) methodology;

(3) Chapter 4 shows the interpretable and logical process of DCM conceptual model generation, which proves the effectiveness of EBD;

(4) In chapter 5, the validation of EBD is presented through its application of QMS development in an industrial project;

(5) Chapter 6 concludes this thesis and points out future work.

Chapter 2 **Literature review**

2.1 Design Methodology

Comparing to long history of design practices, the study of design theory as a scientific discipline is quite young. This study becomes more and more important because of an increasing need of "Best Design Practice" in optimizing the available yet limited resources for the benefit of mankind (Zeng, 2004). A good design cannot be achieved unless designers are armed with both profound tactic design knowledge and a sound design methodology (explicit or implicit). As a result, a variety of design theories and methodologies have been proposed in the last several decades, such as general design theory (GDT) (Yoshikawa, 1981), theory of inventive problem-solving (TRIZ) (Altshuller, 1984), the systematic design methodology (G.Pahl, W.Beitz et al., 1988; Hubka and Eder, 1988), axiomatic design (Suh, 1990), total design (Stuart, 1991), decision-based design (Hazelrigg, 1996), formal design theory (Braha and Maimon, 1998), decision-made deign (Hazelrigg, 1996; Hazelrigg, 1998), axiomatic theory of design modeling (Zeng, 2002), adaptable design (Gu, Hashemian et al., 2004), and affordance based design (Maier and Fadel, 2009).

General Design Theory (GDT) is a mathematical theory of design, which is proposed by Yoshikawa for the development of advanced CAD (computer-aided design) and for innovative design from the research results of a group (Tomiyama, 1994). GDT tries to explain how design is conceptually performed with knowledge manipulation. It formalizes design knowledge based on axiomatic set theory. GDT considers that a design process could be represented by three axioms: Axiom 1 (axiom of recognition) ; Axiom 2 (axiom of correspondence); Axiom 3 (axiom of operation) (Tomiyama, Gu et al., 2009).

However, GDT assumptions are too restrictive to apply directly to design, and several potential avenues for modifying the theory to attempt to broaden its scope need to be explored (Reich, 1995).

The Theory of Inventive Problem Solving (TRIZ) is developed by G.S. Altshuller and his school in the former USSR, based on an extensive study of the World Patent Database(Savransky, 2000). It is a human-oriented knowledge-based systematic methodology of inventive problem solving, which includes a series of powerful tools to detect the search for solutions to engineering problems (1996). TRIZ relies on deep knowledge and provides possibilities for effective solutions of difficult problems.

The systematic design methodology was developed by the German professors Pahl and Beitz in the 1970s (Hubka and Eder, 1988). In this methodology, the design process is divided into four phases: product planning and clarifying the task; conceptual design; embodiment design; and detail design. Systematic procedures help to render designing comprehensible and make the subject easy to learn. This methodology supplies an effective way to rationalize the design and product processes.

The axiomatic approach to design provides a general theoretical framework for all design fields. The theory is applicable to many different kinds of systems, including machines, large systems, software systems, organizations, and systems consisting of a combination of hardware and software (Suh, 1998). There are three key concepts of axiomatic design: the existence of domains, the characteristic vectors within the domains that can be decomposed into hierarchies through zigzagging between the domains, and the design axioms (Suh, 1995). According to these design axioms, corollaries and theorems can be stated or derived for simple systems, large systems, and organizations.

These theorems and corollaries can be used as design rules or guidelines for designers.

The methodology of total design provides a design framework for a structured design process model, which is the application of design methodology in design practice (Stuart, 1991). It uses Concept Selection Process to choose the best concept from a series of candidates according to some criteria using a Pugh Matrix. It can be used not only in overall conceptual design process, but also for concept decision of system components. The total design of Pugh is easy and simple to use by designers, in another hand, although it develops independently from Quality Functional Deployment (QFD), it can be easily integrated into QFD.

Formal Design Theory (FDT) is a mathematical theory of design. It wants to develop a domain independent core model of the design process. FDT explores some issues, for example, the algebraic representation of design artefacts, idealized design process cycle, and computational analysis and measurement of design process complexity and quality (Braha and Maimon, 1998).

Axiomatic Theory of Design Modelling is established for studying design (Zeng, 2002). According to this theory, a formal model of design could be derived to represent the syntactic structure of hierarchical evolving design objects and the dynamic design process. It usually focuses on the general design problem and the general model of design, so models for concrete design problems can be logically deduced. The top-down approach can be used as a formal logic and scientific tool to derive formal design theories and computational design models. In addition, it can be used to organize designers' activities and to implement various CAD systems. However, the top-down axiomatic approach has not yet been as popular and thus as fruitful as other approaches in the modelling design, because it needs much longer time to mature, and its usefulness is usually invisible in the early stages of development.

Engineering design is increasingly recognized as a decision-making process. This recognition brings with it the richness of many well-developed theories and methods from economics, operations research, decision sciences, and other disciplines (Hazelrigg, 1998). Decision-Based design applies the rules of decision theory in a design decision-making process in order to maximize the value of a designed artefact (Hazelrigg, 1996). It forces the engineering design process into a total systems context, and requires any design decisions should be responsible for a product's total life cycle. In addition, it is the foundation of design that is based on a rigorous set of axioms. However, because of the rigor of decision-based design which places stringent conditions on the process of engineering design, the popular approaches such as Quality Function Deployment are eliminated.

Adaptable design (Gu, Hashemian et al., 2004) is a new design approach that aims at creating designs and products that can easily meet different and changing requirements. Since the design requirements or the operating environment of products are always changing, the efforts of design and product adaptation are very important. Therefore, the design and product adaptability should be considered at the design stage and the adaptable design, a design methodology for ease of adaptation of design or product considering changes in requirements, is necessary (Tomiyama, Gu et al., 2009).

A relational theory of design is needed, since traditional design methodologies are based on the transformative concept of function, which limits the scope of design problems and explanatory power of current design theory. Affordance based design is a relational theory for design based on the concept of affordances from perceptual psychology. It can help to explain the entanglement relationships between designers, users, and artefacts, which cannot be handled by the function based approaches of design (Maier and Fadel, 2009).

2.2 Validation of Effectiveness

According to West, the broader definition of effectiveness still focuses on the extent to which effort "meets its objectives" (West, (Cedefop) et al., 1999). Fraser (Fraser, 1994) defined effectiveness is a measure of the match between stated goals and their achievement. Erlendsson (Erlendsson, 2002) argued effectiveness as the extent to which objectives are met ('doing the right things'). The United Nations Educational, Scientific and cultural Organization (UNESCO) definition is an output of specific analyses that measure the quality of the achievement of a specific goal or the degree to which the results can be expected to achieve specific requirements (UNESCO, 2008). Wojtczak (Wojtczak, 2002) claimed that effectiveness is a measure of the extent to which a specific goal does what it is intended to do. Therefore, effectiveness is the capability of producing an effect to which an activity fulfils its intended purpose or function.

The validation of design methodologies is important for the continuing development of design methods. The validation processes can guide the improvement and evaluation of new methods (Frey and Dym, 2006). The concept of validation defined by the Institute of Electrical and Electronics Engineers (IEEE, 1998) is the "confirmation by examination and provision of objective evidence that the particular requirements for on intended use are fulfilled".

There are several ways on validation in the context of design methodology. Schon and Argyris (Argyris and Schon, 1974) proposed a framework for evaluating design methodology including four aspects: internal consistency, congruence with the espoused theory, testability of the theory, and effectiveness of the theory. Pedersen (Pedersen, Pedersen et al., 2000) introduced a similar framework which can check the design methodology form four design dimensions: (1) Theoretical structural validity. (2) Empirical structural validity. (3) Empirical performance validity. (4) Theoretical performance validity. There are three prominent contemporary views of the justification of knowledge claims for Audi (Audi, 1995): foundationalism, relativism and naturalistic epistemology. An alternative definition of validation proposed by Olewnik and Lewis (Olewnik and Lewis, 2005), for a method to be valid, includes three criteria: the design method must be logical; use meaningful reliable information and not bias the designer.

2.3 Formulization in Design Chain Management

Clark (Clark and Fujimoto, 1991) and Twigg (Twigg, 1997) positioned a design chain as the relationship between a product assembler and its part suppliers. Poirier and Reiter adapted the concept of design chain to product development chain, which is a system through which organizations develop products and services to meet customer requirements (Poirier and Reiter, 1996). O’Grady indicated that the product development chain encompasses product assembler, the suppliers and the customers (O'Grady and Chuang, 2001). There may be a considerable mesh of suppliers to suppliers, called second-tier suppliers, third-tier suppliers and so on (O'Grady and Chuang, 2001; Muckenhirn and Meier, 2008). It is generally agreed that design chain involves participants throughout the product development process, from concept, detail engineering, process engineering, prototype manufacturing, through to post-launch activities (Twigg, 1998). Each participant, both internal and external to a focal firm, contributes their capabilities (knowledge and expertise) necessary for design and development of a product (Twigg, 1997).

Effective design chain management is of paramount importance for industries to develop innovative and high quality products within a reduced lead-time and cost (Garg, ; Ajoku, 2007). Research in this field is mainly concerned with the early involvement of suppliers in new product development (Carlisle and C., 1989; Dowlatshahi, 1998; Akira, 2001), selecting suitable design chain partners for co-development success (Nagarajan, Passey et al., 2004; Wang and Zeng, 2009; Kuei, Madu et al., 2011), the design processes collaboration in the design chain (Choi, Kim et al., 2005; Shiau and Wee, 2008), and the cross-industry diagnostic tool for design-chain management- Design Chain Operation Reference-model (DCOR) (Supply-Chain-Council, 2004) as well as its extension (Wu, Yeh et al., 2007). All those research results come from researchers' ad-hoc observations. In order to develop more robust tools to support design chain management, the design chain management (DCM) needs to be modelled based on a formal foundation.

Respective design chain management reference models have been developed to tackle design process and operations (Supply-Chain-Council, 2004; Choi *et al.*, 2005; Wu *et al.*, 2007), design authorities distribution (Twigg, 1998), supplier performance measurement (Nagarajan *et al.*, 2004), collaboration strategy (Chuang and Yang, 2004), process change management (Shiau and Wee, 2008), process maturity model (Fraser *et al.*, 2003). The process maturity model (Fraser, 1994) improves product development collaboration in the design chain by properly managing the development processes and the communication plans between partners. The integration mechanisms model (Twigg, 1998) aims coordinating supplier-manufacturer joint design activities from technology, organization, and procedure aspects during the pre-project, design, and manufacturing phases. The design chain conceptual model (PRTM model) (Deck and Strom, 2002) develops a good strategy for the design of a design chain that will have a governance structure to facilitate the collaborative work between partners. The standard DCOR model (Supply-Chain-Council, 2004) tries to identify the principal process elements in the design chain, as a reference for firms to analyze and to improve design chain performance. The design chain collaboration complexity trend model (Chuang and Yang, 2004) establishes design chain collaboration strategies. The performance measurement framework (Nagarajan, Passey et al., 2004) assesses supplier capability and compatibility in terms of design chain processes, tools and techniques. The product design chain collaboration framework (Choi, Kim et al., 2005) resolves major obstacles to collaboration during product design by offering design process reference model based on SCOR, service component reference model, technology and standard reference model. The collaborative design chain operations reference model (Wu, Yeh et al., 2007) develops a collaborative design chain system in the product lifecycle. The distributed change control workflow (Shiau and Wee, 2008) maintains the consistence among designs in a collaborative design network.

2.4 Development of Quality Management System

The traditional method to develop a QMS is starting with identifying the key criteria and related procedures, actions, and tools to assess whether a facility has a quality management system. Then, according to the requirements of QMS, provider begins to develop their own quality management system. Some theories and methodologies have been proposed in the last several decades to help developing quality management systems.

A new theory is introduced that Six Sigma can be seen as a methodology for total quality management system (Klefsjö, Wiklund et al., 2001). In this theory, Six Sigma is a methodology within the larger framework of total management. It can be noted that Six Sigma supports all TQM values and also illustrates that the management system is dynamic. Therefore, Six Sigma is a methodology can be used to develop quality management system. It may help choose the tools and support the values of organizations, in order to cut organizations' costs.

Advanced Product Quality Planning (APQP) – concept belonging to standardized quality management is often used in designing, understanding and mastering product quality planning (Bobrek and Sokovic, 2005). In order to assure the product satisfies customer, all required steps should be completed in time. Based on the APQA model, it is possible to define design tasks for management systems design in the following manner: design base foundation which includes strategic analysis and recognition, operational goals analysis and recognition, input-output relations analysis and recognition, laws and standards requirements analysis and recognition; process model design which includes transformations process design, measurements and control systems design, data capture and analysis system design, testing and decision making processes design, and management resource procedures design; design of the applicative model of the management system which include system integration and management system documentation. It implements active procedure in the field of human resource management to overcome the disadvantage of the systems approach in quality management design.

A new methodology (Lau, Ho et al., 2009) is presented as a tool to discovering the hidden relationships among all the process variables in development of quality management system. The algorithm is proposed to extract interesting patterns in terms of fuzzy rules, from centralized process data stored as quantitative values based on the concept of fuzzy set and association rule method. This intelligent system standardizes the process data exchange format for identifying potential process problems. Therefore, it can lead to get the high-quality products with the lowest cost and fewest resources. Also, it has the ability to monitor the process effective, efficient, and adaptable.

Vainio and Mattila developed a model of total quality management system (Vainio and Mattila, 1996) through group work for an electricity company. The group work is the place where the supervisors and employees in question participated. The total quality handbook was written based on ISO 9001 and ISO 9004-2, and includes safety and ergonomics instructions and safety and ergonomics requirements.

ISO 9000 is used to help the companies to improve quality in terms of work procedures, product and service quality, team spirit, subcontractor control, efficiency and complaints (Lee, Leung et al., 1999). Since some companies want to continuously improve their quality on the basis of a quality management system, some of them do not know how to start. Lee, Leung and Chan review the difference between normal practice and the ISO 9000 requirements and give some recommendations.

Houston and Rees (Houston and Rees, 1999) developed a quality management system for a postgraduate education programme in1999. They used several methods for developing this QMS. For example, literature search, project group discussions, informal and formal meetings with academic staff and students, flow charting processes, matrix mapping to make comparisons and the assimilation of existing quality and other written material. Also, they compare the programme with quality system standard (ISO 9001) in order to establish an appreciation from a quality management perspective.

Matthews (Matthews, 2001) introduced a case study about implementing quality management systems in an academic department in a higher education institution. This QMS is implemented based on action research, which is an approach for organizational change and management development based on combining action with research. This action-research cycle includes five steps: review of situation; diagnosis; planning of remedial action; implementation; and the observation, reflection and monitoring of the change (winter and Burroughs, 1989). The case study in this paper uses action research to formulize and carry out of a self-assessment process to quality systems.

Yang (Yang, 2006) developed a quality management system which is based on sound theoretical and pragmatic considerations. He generated an innovative and comprehensive quality management system as a useful benchmarking reference for service organization. The present study shows the steps to establishing a quality management system: mission and vision; target market segments and positioning; strategic planning and management; customer focuses; define quality policy and target objectives; design service delivery and support system. Also, strategic planning, balanced scorecard, Six Sigma, and total quality management can be used to develop quality management system.

Chapter 3 **Environment Based Design**

3.1 Introduction

Intuitively, design is a human activity that aims changing an existing environment to a desired one by creating a new artifact into the existing environment (Zeng, 2004; Zeng, 2004). Environment-Based Design (EBD) is such a design methodology that provides step-by-step procedures to guide a designer throughout this environment change process. The underlying principles behind the EBD are that design comes from the environment, serves for the environment, and goes back to the environment. EBD was logically derived from the observation above following the axiomatic theory of design modeling (Zeng, 2002). As illustrated in Figure 1, the EBD includes three main activities: 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.

This section will give an overview of the EBD methodology. The first subsection will be focused on the EBD process whereas some fundamentals of EBD will be explained in the second section.

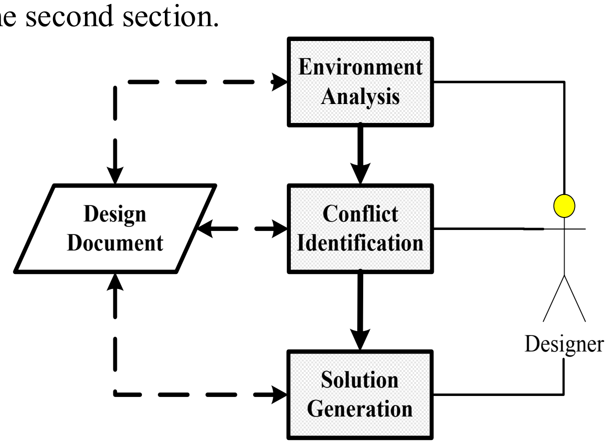

Figure 1 Environment Based Design: process flow(Zeng, 2004).

3.2 Environment Based Design (EBD)

Mathematically, the EBD process can be represented by structure operation, denoted by ⊕. Structure operation can be defined as the union (∪) of an object O and the interaction (⊗) of the object with itself (Zeng, 2004).

$$\oplus O = O \cup (O \otimes O), \quad (1)$$

where ⊕O is the structure of the object O. Everything in the universe can be seen as an object. Interactions between objects are also objects. Examples of interaction include force, movement, and system input and output. Structure operation provides a means to represent a hierarchical system with a single mathematical expression. The application of structure operation can be found in the representation of sketches (Zeng, Pardasani et al., 2004) and linguistic information in design (Zeng, 2008).

Due to the capacity of human cognition and the scope of an application, a group of primitive objects can always be defined as (Zeng, 2002; Zeng, 2008)

$$\oplus O_i^a = O_i^a. \quad (2)$$

Equation (2) means that a primitive object is an object that cannot or need not to be further decomposed.

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

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

It has been shown that the environment structure, which is $\oplus E$, includes the description of the design solution at design stage i and the design requirements for the design stage i+1 (Zeng, 2004)

Therefore, the EBD process can also be graphically illustrated in Figure 2, which implies the recursive evolution of design requirements and design solution (Zeng and Cheng, 1991; Zeng and Jing, 1996).

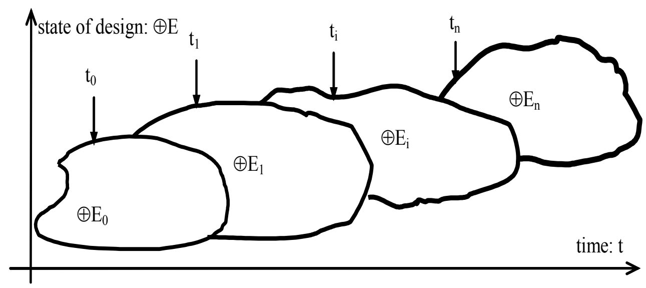

Figure 2 Environment Based Design: process (Zeng, 2004)

3.2.1 Environment Analysis

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

$$\oplus E_i = \oplus \left(\bigcup_{j=1}^{n_e} E_{ij}\right) = \bigcup_{j=1}^{n_e}(\oplus E_{ij}) \cup \bigcup_{j_1=1}^{n_e} \bigcup_{\substack{j_2=2 \\ j_2 \neq j_1}}^{n_e} \left(E_{ij_1} \otimes E_{ij_2}\right), \quad (4)$$

Where n_e is the number of components included in the environment E_i at the i^{th} design state; E_{ij} is an environment component at the same design state. It should be noted that decisions on how many (n_e) and what environment components (E_{ij}) are included in E_i depend on designer's experience and other factors relevant to the concerned design problem.

Environment is a compound object including its components and the relationships between those components. Since all product requirements come from the relevant environment, clearly and correctly identifying environment components is critical for a successful design. The objective of environment analysis is to identify the environment in which the desired product is to work (Zeng, 2004). From the environment implied in a design problem described by the customers, the designer will introduce extra environment components that are relevant to the design problem at hands. Results from this analysis constitute an environment system.

In the environment analysis section, by using Recursive Object Model (ROM) (Zeng, 2008), question asking strategy, the whole environment system will be broken down into sub-systems, and each sub-system will be decomposed into smaller components until these components are proper for defining the current environment system.

3.2.2 Conflict Identification

Activity 2: Conflict identification: identify undesired conflicts C_i between environment components by using evaluation operator K_i^e , which depends on the interested environment components.

$$C_i \subset K_i^e\left(\bigcup_{j_1=1}^{n_e} \bigcup_{\substack{j_2=1 \\ j_2 \neq j_1}}^{n_e} \left(E_{ij_1} \otimes E_{ij_2}\right)\right). \tag{5}$$

Conflicts are considered as the driving force in the EBD process (Zeng, 2004). From the updated ROM diagram that developed in environment analysis, potential conflicts may exist between environment components, as well as in the relations between these components. As shown in Figure 3, there are three forms for an existing conflict in a ROM diagram: conflict between two objects, conflict between two constraint relations, and conflict between two predicate relations (where A, B means objects, R and C represent relations between objects and the conflict respectively). Design conflicts can be identified by iteratively applying the three forms to a ROM diagram for a design problem. Design conflicts can be identified by iteratively applying the three rules (see Table 1) to the ROM diagram for a design together with the semantics of the constrains or predicates. However, the rules shown in Table 1 are not complete and inclusive.

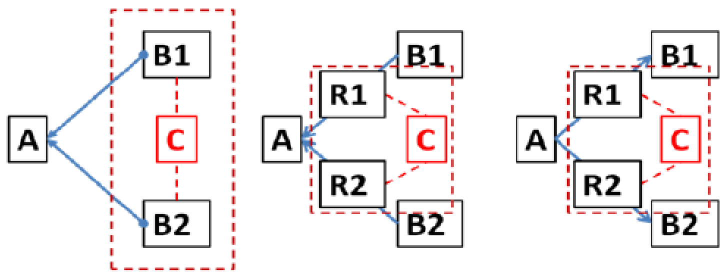

Figure 3 Three Rules for Conflict Identification from a ROM Diagram (Zeng, 2004)

Table 1 Rules for Identifying Potential Conflicts (Zeng, 2004)

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 other objects, then potential conflict exists between a pair of those predicate relations
Rule 3:	If an object has multiple predicate relations to other objects, then potential conflict exists between a pair of those predicate relations

3.2.3 Solution Generation

Activity 3: Solution generation: generate a design solution s_i by resolving a group of chosen conflicts through a synthesis operator K_i^s. The generated solution becomes a part of the new product environment for the succeeding design.

$$\exists C_{ik} \subset C_i, K_i^s : c_{ik} \rightarrow s_i, \oplus E_{i+1} = \oplus (E_i \cup s_i). \quad (6)$$

The design process above continues with new environment analysis until no more undesired conflicts exist, i.e., $C_i = \Phi$.

Before giving solutions to identified conflicts, the designer should analyze them first. The principle is to figure out dependences among potential conflicts as one conflict may be resulted from others. Tracing back to the root where the most basic conflict exists, and handling root conflicts first may eliminate some consequent conflicts that depend on it. Effective solutions can be generated in this manner. With the generated solutions, the ROM diagram, which represents the original design problem, is updated again. Repeat the process until no more undesired conflicts exist.

In generating design solutions, a design process was divided into two parts: atomic design and the recursive resolution of complex design problem (Zeng and Cheng, 1991). Atomic design is where knowledge is available or can be systematically discovered to resolve a conflict. Hence, it depends on the designer's experience and background. Obviously, an experienced designer can have a more complex atomic design than a novice. Recursive resolution of a complex design problem can be conducted through environment decomposition, which will identify the key conflict to start with.

3.3 Fundamentals for Applying EBD

3.3.1 Recursive Object Model (ROM)

As shown in the last subsection, environment structure can be used to represent design mathematically throughout the design process. A critical component in the structure operation is the interaction operation. To facilitate the application of the structure operation, the Recursive Object Model (ROM) is proposed to represent the information appeared in design (Zeng, 2008). The ROM includes two kinds of objects, which are primitive and compound objects, and three kinds of relations: constraint, predicate and connection. Table 2 shows the graphic symbols in the ROM.

ROM is a fundamental tool of the EBD. In environment analysis, designers transform original design problem and requirements described in natural language into a ROM diagram. The transformation enables the designer to define and understand the design problem more clearly. In conflict identification, a ROM diagram can show the relations between environment components intuitively, which can be used to identify the root conflict.

Table 2 Types of Symbols in ROM (Zeng, 2008)

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

3.3.2 Question Asking Approach

Product requirements are descriptions of the desired solution to a design problem. In engineering design, just as in all other design problems, the efficient, precise, and complete specification of design requirements is critical if designers are to deliver a quality design solution within a reasonable range of cost and time (Wang and Zeng, 2009). Therefore, another main tool used in the EBD is question asking approach. How to ask proper questions is critical for collecting right product requirements and having a correct understanding of current system.

There are two types of questions should be asked based on the developed ROM diagram in environment analysis. The first is generic question for the clarification and extension of the meaning of the design problem whereas the second is domain specific question for implicit design information related to the current problem (Wang and Zeng, 2009). The generic questions are based on linguistic analysis of the description of a design problem. They help designer to better understand the design problem. The domain specific questions are based on the life cycle of design product. The purpose of asking domain specific questions is to collect information that would have significant influence on the design problem.

3.3.3 Classification of Product Environment

In order to further verify the completeness of the extracted environment components and their relations, a roadmap was proposed as guidance for requirements modeling (Chen and Zeng, 2006). In this roadmap, 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 the product life cycle whereas the other classifies them by partitioning the product environment into natural, built, and human environments (Zeng, 2011). For their case, Chen and Zeng (2006) divided the life cycle into seven kinds of events, which were design, manufacture, sales, transportation, use, maintenance, and recycling. The requirements were fit into the seven events. At any time point of product life, one or some of these seven events might occur simultaneously or alternatively (Chen and Zeng, 2006). On the other hand, as illustrated in Figure 4, they classified the product requirements into three environments: natural environment, human environment and built environment. In this pyramid-like model, requirements at the lower levels have higher priority in the development of a design solution while those products meeting the requirements at the highest level are said to be called high usability products (Zeng, 2004). They pertain to the purposes of the human use of the product (Wang and Zeng, 2009); the lowest level of product requirements comes from the natural environment; and the rest are the result of the built environment. Although product life cycle varies from product to product, by following the roadmap, the implicit requirements can be found, which gives the designer a very detailed "whole picture" about the design problem.

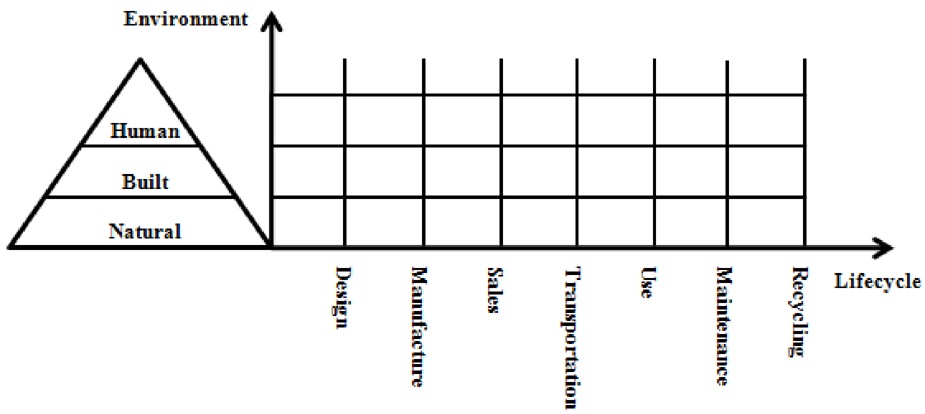

Figure 4 Roadmap for Product Environment Classification

Chapter 4 **Formalization of Design Chain Management**

4.1 Introduction

It is fairly well known that up to 80% of product cost is determined by the decisions made in the early design stages; therefore, effective management of product design plays an important role in the entire product lifecycle. In the last two decades, product design activities have been moving to a collaborative environment across extended enterprises, due to the advancement of technologies, the globalization of markets, the segregation of customer demands, and the competition at home and abroad.

This chapter intends to develop a formal conceptual model of design chain management through formalizing the design chain system and by identifying its underlying problems and available management approaches. This task is taken as a design problem where the design solution is the formal conceptual model of design chain system of an informal description of design chain management, which is generic and ill–defined. The application of EBD to solving this ill-defined problem proves the effectiveness of EBD.

4.2 Conceptual Model of DCM

The purpose of formalization is to turn the informal into a formal structure. In this section, we will start with an informal definition of DCM and finish with a formal conceptual model of the DCM. The Environment-Based Design (EBD) methodology is adopted to formalize the design chain management.

The informal definition of DCM is described as follows: The term Design Chain Management was defined as the management of the participants, both internal and external to a focal firm that contributes the capabilities (knowledge and expertise) necessary for the design and development of a product which, on completion, will enable full-scale manufacture to commence (Twigg, 1998). Consequently, the design chain involves participants throughout the product development process, from concept, detail engineering, process engineering, prototype manufacturing, through to post-launch activities (Twigg, 1998), including designers, suppliers, manufacturers and customers.

The following subsections will show the EBD process of formalizing the definition above into a formal DCM conceptual model.

4.2.1 Environment Analysis

According to the EBD, a design problem is implied in the environment in which the product is expected to work. The objective of environment analysis is to identify the environment components and their relations implied in a design problem.

Environment can be generally classified into natural, built, and human environments, denoted by E^n, E^b, and E^h, respectively (Zeng, 2002). Human environment refers to everyone who has a direct impact on the system; natural environment represents every natural aspect that is not subject to human control; and built environment includes every creation of human being that directly affects the system.

$$\oplus E = \oplus \left(E^n \cup E^b \cup E^h\right). \qquad (7)$$

Therefore, the first step in formalizing the DCM is to identify the major components and their relations implied in the informal definition of the DCM. This can be achieved by generating the ROM diagram for the informal definition, which is shown in Figure 5.

Figure 5 can be simplified into Figure 6 following the rules defined in Zeng (Sun, Feng et al., 2010), which can show the structure of DCM system clearly.

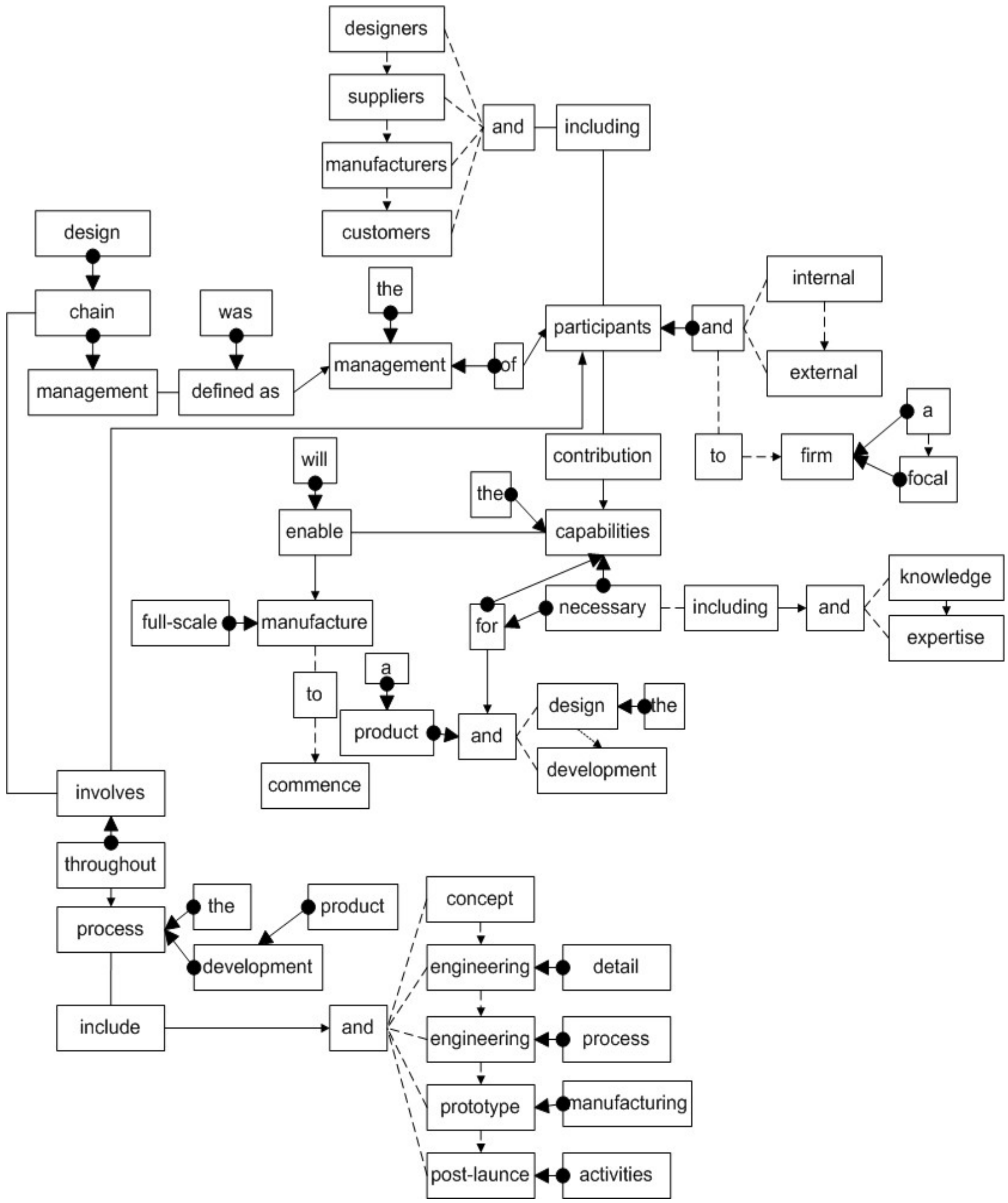

Figure 5 ROM Diagram of Informal Definition of DCM

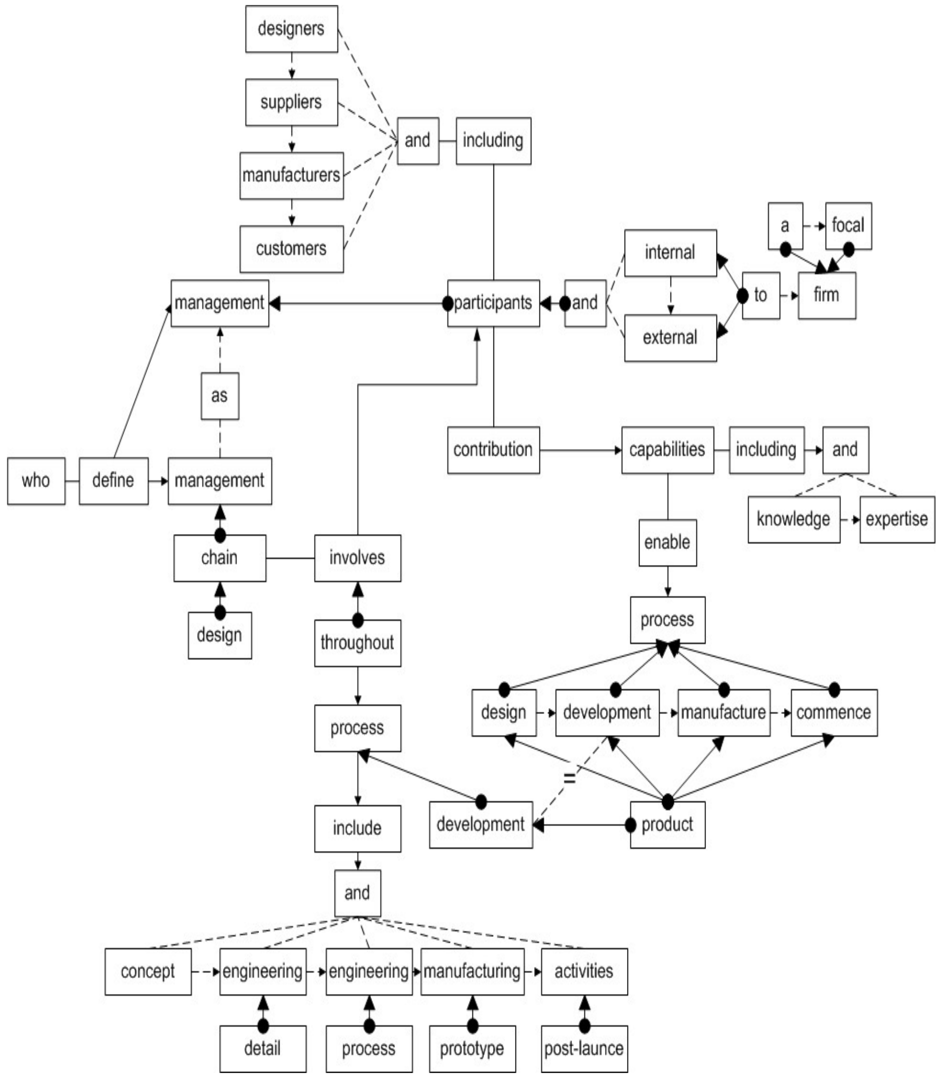

Figure 6 Simplification of ROM Diagram for DCM Definition

From this ROM diagram, it is clear that the main objects are 'participant', 'capability' and 'process' since they have the most constraint relations. Furthermore, the most critical constraining objects are 'firm' and 'product'. These five objects constitute the first level of environment components, as is given in Table 3. They can be seen as primitive objects as defined in Equation (2), that is,

$$\oplus \mathrm{E_i} = \mathrm{E_i}, \forall \mathrm{i} = 1, \ldots, 5. \qquad (8)$$

The relations between these five components are given in the Table 4.

Table 3 Environment Components – 1

E_1	E_2	E_3	E_4	E_5
participant	process	capability	product	firm

Table 4 Relations between Components – 1

	E_1	E_2	E_3	E_4	E_5
E_1		plan, execute, monitor …	contribute	control, manage	constitute, manage …
E_2	influenced by		influenced by	contribute	owned by
E_3	belong to	enable		determine	contribute
E_4	produced by	influenced by	influenced by		developed by
E_5	contain	manage, control …	influenced by	control, manage …	

Mathematically, the ROM diagram shown in Figure 5 and Figure 6 are part of the following structure.

$$\oplus\Omega = \oplus\,[(E_1 \cup E_2 \cup E_3) \cup (E_4 \cup E_5)]. \tag{9}$$

Applying Equation (1) to Equation (9), we get

$$\begin{aligned}\oplus\Omega &= [\oplus(E_1 \cup E_2 \cup E_3)] \cup [\oplus\,(E_4 \cup E_5)] \cup [(E_1 \cup E_2 \cup E_3) \otimes (E_4 \cup E_5)] \\ &\quad \cup [(E_4 \cup E_5) \otimes (E_1 \cup E_2 \cup E_3)] \\ &= [(\oplus\, E_1) \cup (\oplus\, E_2) \cup (\oplus\, E_3) \cup (E_1 \otimes E_2) \cup (E_1 \otimes E_3) \cup (E_2 \otimes E_1) \cup \\ &\quad (E_2 \otimes E_3) \cup (E_3 \otimes E_1) \cup (E_3 \otimes E_2)] \cup [(\oplus\, E_4) \cup (\oplus\, E_5) \cup \\ &\quad (E_4 \otimes E_5) \cup (E_5 \otimes E_4)] \cup [(E_1 \otimes E_4) \cup (E_1 \otimes E_5) \cup (E_2 \otimes E_4) \cup \\ &\quad (E_2 \otimes E_5) \cup (E_3 \otimes E_4) \cup (E_3 \otimes E_5) \cup (E_4 \otimes E_1) \cup (E_4 \otimes E_2) \cup \\ &\quad (E_4 \otimes E_3) \cup (E_5 \otimes E_1) \cup (E_5 \otimes E_2) \cup (E_5 \otimes E_3)].\end{aligned} \tag{10}$$

According to Equation (8), Equation (10) can be further simplied as

$$\begin{aligned}\oplus\Omega = & [E_1 \cup E_3 \cup (E_1 \otimes E_2) \cup (E_1 \otimes E_3) \cup (E_1 \otimes E_4) \cup (E_1 \otimes E_5) \cup \\ & (E_3 \otimes E_1) \cup (E_3 \otimes E_2) \cup (E_3 \otimes E_4) \cup (E_3 \otimes E_5)] \cup [E_2 \cup (E_2 \otimes E_1) \cup \\ & (E_2 \otimes E_3) \cup (E_2 \otimes E_4) \cup (E_2 \otimes E_5)] \cup [E_4 \cup (E_4 \otimes E_1) \cup (E_4 \otimes E_2) \cup \\ & (E_4 \otimes E_3) \cup (E_4 \otimes E_5)] \cup [E_5 \cup (E_5 \otimes E_1) \cup (E_5 \otimes E_2) \cup (E_5 \otimes E_3) \cup \\ & (E_5 \otimes E_4)] \\ = & \mathbf{M_{ts}} \cup \mathbf{M_{pc}} \cup \mathbf{M_{pd}} \cup \mathbf{M_{pm}}, \qquad (11)\end{aligned}$$

Where

$$M_{ts} = [E_1 \cup E_3 \cup (E_1 \otimes E_2) \cup (E_1 \otimes E_3) \cup (E_1 \otimes E_4) \cup (E_1 \otimes E_5) \cup (E_3 \otimes E_1) \cup$$

$$E3 \otimes E2 \cup E3 \otimes E4 \cup E3 \otimes E5. \qquad (12)$$

$$M_{pc} = [E_2 \cup (E_2 \otimes E_1) \cup (E_2 \otimes E_3) \cup (E_2 \otimes E_4) \cup (E_2 \otimes E_5)]. \qquad (13)$$

$$M_{pd} = [E_4 \cup (E_4 \otimes E_1) \cup (E_4 \otimes E_2) \cup (E_4 \otimes E_3) \cup (E_4 \otimes E_5)]. \qquad (14)$$

$$M_{pm} = [E_5 \cup (E_5 \otimes E_1) \cup (E_5 \otimes E_2) \cup (E_5 \otimes E_3) \cup (E_5 \otimes E_4)]. \qquad (15)$$

Hence, the structure of DCM environment can be represented as the union of the structure of participant, process, capability, product, firm, as well as the relations among them. This structure is given in Equation (11) and illustrated in Figure 7, which can be further refined by decomposing its components.

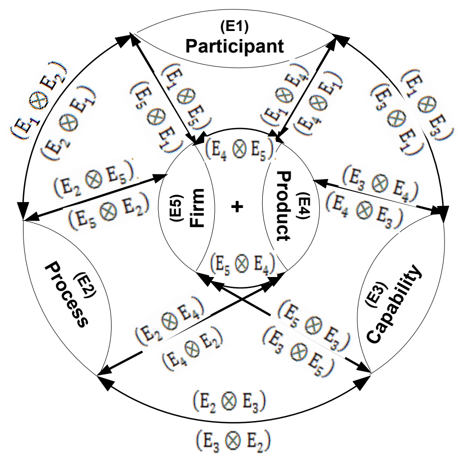

Figure 7 Structure for Conceptual Model of DCM

4.2.2 Conflict Identification and Solution Generation

In the DCM environment, from Table 4, it is obvious that the relations between environment components are independent, which means there is no conflict in the current DCM system. Further problems of the design may come from the decomposition of the identified environment components.

4.3 Interpretation of the Formal Model

In Equation (11), M_{ts} means that participant (E_1) needs to take into account capability (E_3) of all relevant cycles, such as sources, time, technology and so on, in order to work out a reasonable and feasible work task. This leads to a task centered model in the DCM. M_{pc} shows all the related processes in DCM, and the involved participants, the necessary capabilities in different processes, as well as the relations between them. For example, the designers in design process and the manufacturers in engineering process. That means a process centered model is needed in DCM. Similarly, M_{pd} shows product and the relations between product and other primitive objects, so the product is a very important object in DCM which should be focused on; hence, a product centered model is necessary. M_{pm} represents the focal firm and the relations between the firm and other objects in DCM, which pays close attention to the performance of the whole DCM system and show the reason why a performance centered model is important in DCM.

Consequently, DCM can be regarded as a management process, providing a set of solutions to address various unacceptable conflicts among the relations between its environment components. A representative model of design chain management can be derived as

$$
\begin{aligned}
S_{DCM} &= \oplus\left(M_{ts} \cup M_{pc} \cup M_{pd} \cup M_{pm}\right) \\
&= (\oplus M_{ts}) \cup \left(\oplus M_{pc}\right) \cup \left(\oplus M_{pd}\right) \cup \left(\oplus M_{pm}\right) \\
&\quad \cup \left(M_{ts} \otimes M_{pc}\right) \cup \left(M_{ts} \otimes M_{pd}\right) \cup \left(M_{ts} \otimes M_{pm}\right) \\
&\quad \cup \left(M_{pc} \otimes M_{ts}\right) \cup \left(M_{pc} \otimes M_{pd}\right) \cup \left(M_{pc} \otimes M_{pm}\right) \\
&\quad \cup \left(M_{pd} \otimes M_{ts}\right) \cup \left(M_{pd} \otimes M_{pc}\right) \cup \left(M_{pd} \otimes M_{pm}\right) \\
&\quad \cup \left(M_{pm} \otimes M_{ts}\right) \cup \left(M_{pm} \otimes M_{pc}\right) \cup \left(M_{pm} \otimes M_{pd}\right), \qquad (16)
\end{aligned}
$$

where again M_{ts} represents a task centered model; M_{pc} represents a process centered model; M_{pd} represents a product centred model; and M_{pm} represents a performance centered model.

4.4 Refinement of DCM Conceptual Model

According to Equation (16), the structure of conceptual DCM model – Wheel Model can be generated as in Figure 8. In this wheel model, four different types of models – task centered model, process centered model, product centered model and performance centered model work together to resolve problems in the DCM process from different aspects. Diverse elements and aspects such as involved participations, design process, design chain operation, design chain management process, and design chain collaboration, are taken into account, which are significant for the effective development of potential DCM methodologies or supporting tools. It is called the wheel model since any internal conflict between the components of DCM will lead to an evolution of the model, where the internal conflict is like the torque acting on the wheel of DCM model.

In order to complete the wheel model, the four models included in Equation (16) should be developed. The following derives the product centred model M_{pd}. The EBD methodology is used again to further refine the product lifecycle management (PLM) by decomposing its components.

Liu described components and their relationships in the PLM environment as depicted in Figure 9 (Liu, 2009). It provides the foundation for identifying the components, sub-components and all possible relations about a product in the DCM process.

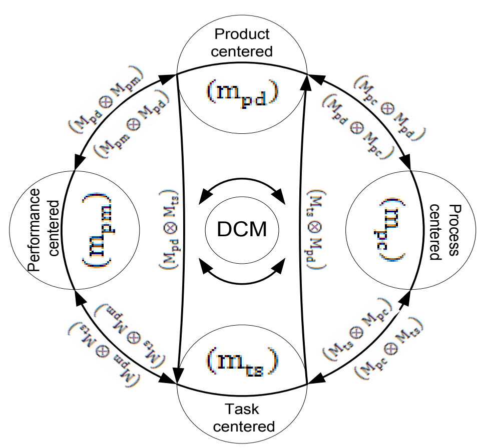

Figure 8 Structure of Wheel Model

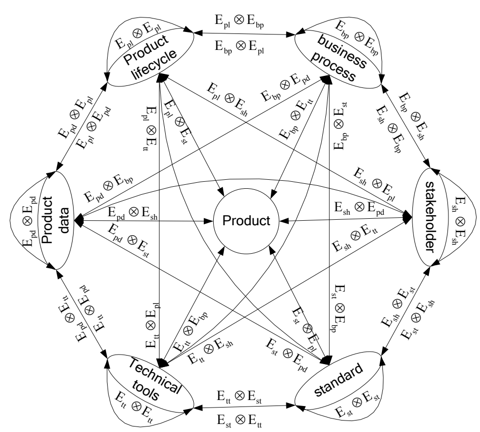

Figure 9 PLM Relational Graph in DCM Environment (Liu, 2009)

4.4.1 Environnent Analysis

Table 5 shows the environment components residing in DCM. The human environment includes all involved participants, such as suppliers, manufacturers, customers, developers, transporters, distributors, maintainers, managers, and recyclers. The natural environment contains natural resources such as time and space. The built environment includes objects such as products, organizations, standards, design data, design knowledge, IT tools, design processes and design strategy.

In the environment of DCM, various relations exist between two components or from a component to itself or among multi-components. Relations can be described in words including design, use, share, inquiry, communication, and so on. In most cases, there are various relations between two components and each relation may have its attributes, properties, features and levels, etc. For example, Clark and Fujimoto (Clark and Fujimoto, 1991) observed the relation of design authority between suppliers and manufacturers, and divided it into three levels: full authority, part authority and no authority, while Twigg extended it to eight levels (Twigg, 1998). According to (Sharma, 2005), at least three categories of relations between human and data can be extracted such as response, requirement/feedback and decision supporting. Furthermore, there are even relations between two relations. Table 6 gives an example to show the relations between E11 developers and other components.

Table 5 Environment Components in PLM

Human environment: E^h	
Design chain participants	E_{11}: developers; E_{12}: manufacturers; E_{13}: distributors; E_{14}: maintainers; E_{15}: suppliers; E_{16}: transporters; E_{17}: recyclers; E_{18}:managers;
Built environment: E^b	
Processes in PLM	E_{21}: requirements; E_{22}:conceptual design; E_{23}: detail engineering; E_{24}: process engineering; E_{25}: prototype manufacturing; E_{26}: testing; E_{27}: goal; E_{28}: strategy; E_{29}: performance;
Product design information	E_{31}: configuration; E_{32}: specification; E_{33}: BOM; E_{34}: engineering changes; E_{35}: cost; E_{36}: parameters;
Product design standards	E_{41}: STEP; E_{42}: PDML; E_{43}: U3D; E_{44}: XML;
IT Tools	E_{51}: SCM; E_{52}: PM; E_{53}: CAD; E_{54}: CAE; E_{55}: PDM; E_{56}: EDM; E_{57}: ERP;
Products	E_{61}: mechanical products; E_{62}: aerospace products; E_{63}: electronic products; E_{64}: service; E_{65}: automatic products;
Natural environment: E^n	
E_{71}: time; E_{72}: space;	

Table 6 Relations between Components

$E_{11} \otimes E_{12}$	communicate, cooperate	$E_{11} \otimes E_{21}$	plan, execute, monitor
$E_{11} \otimes E_{31}$	create, change, share	$E_{11} \otimes E_{41}$	Adopt
$E_{11} \otimes E_{53}$	use	$E_{11} \otimes E_{61}$	Develop
$E_{11} \otimes E_{71}$	spend	$E_{11} \otimes E_{72}$	Consider

4.4.2 Conflict Identification

According to the system component relations identification in the environment analysis part, the relations among the relations between system components are identified. This relation analysis could help find out potential conflicts, which will be resolved in the next step for further analysis. The following table gives an example to show the important possible conflicts which are generated from environment system relations.

Table 7 Conflict Identification

Relations	**Possible conflicts**
$E_{29} \otimes E_{18}, E_{18} \otimes E_{35}$	Collaboration performance and transaction cost (C1)
$E_{12} \otimes E_{15}, E_{15} \otimes E_{29}$	Various suppliers have different ability in product development process(C2)
$E_{12} \otimes E_{32}, E_{15} \otimes E_{32}$	Inconsistency of engineering data due to change (C3)
$E_{11} \otimes E_{36}, E_{15} \otimes E_{36}$	Incompatibility between Information sharing and protection (C4)
$E_{11} \otimes E_{23}, E_{12} \otimes E_{23}$	Inconsistency between design processes of different participants (C5)
$E_{18} \otimes E_{34}, E_{11} \otimes E_{34}$	Incompatible perspectives of different participants (C6)
$E_{14} \otimes E_{26}, E_{14} \otimes E_{26}$	Release more design control authority to increase communication (C7)
$E_{27} \otimes E_{28}$	Process contradictory (C8)
$E_{11} \otimes E_{26}, E_{11} \otimes E_{26}$	Incompatible between different tools (C9)
$E_{11} \otimes E_{27}, E_{12} \otimes E_{27}$	Incompatible goals of different participants (C10)
$E_{11} \otimes E_{28}, E_{18} \otimes E_{28}$	Inconsistent strategies among different participants (C11)

4.4.3 Solution Generation

Blake and Mouton first presented five conflict management styles as problem-solving, smoothing, forcing, withdrawal and sharing (Blake and Mouton, 1970). Thomas later relabeled them and proposed five dimensions of conflict-handling intensions, including avoiding, accommodating, competing, compromising and collaborating (Thomas, 1992). Conflict resolution techniques include problem-solving, super-ordinate goals, expansion of resources, communication, and restructuring the organization. Table 8 gives the corresponding solutions to the conflicts in Table 7.

Table 8 Possible Solution Generation

Conflict descriptions	Suggested Solutions
Collaboration performance and transaction cost (C1)	Web based collaboration software, collaboration performance assessment (S1)
Various suppliers have different ability in product development process(C2)	Design partner selection (S2)
Inconsistency of engineering data due to change (C3)	Collaboration and communication (S3)
Incompatibility between Information sharing and protection (C4)	Collaboration and secure information sharing strategy (S4)
Inconsistency between design processes of different participants (C5)	Mapping existing processes to the predefined process templates (S5)
Incompatible perspectives of different participants (C6)	Collaboration and communication (S6)
Release more design control authority to increase communication (C7)	Centralization (S7)
Process contradictory (C8)	Process collaboration and coordination (S8)
Incompatible between different tools (C9)	Standardization and coordination (S9)
Incompatible goals of different participants (C10)	Goals collaboration (S10)
Inconsistent strategies among different participants (C11)	Strategies collaboration and communication (S11)

Therefore, according to all the conflicts obtained from conflict identification and corresponding solutions stemmed from solution generation, a PLM model is derived, as shown in Figure 10. It must be noted that there can be more conflicts in the PLM process than those listed in Table 7 and Table 8, which are just examples to show how to get the product centred model by using the EBD.

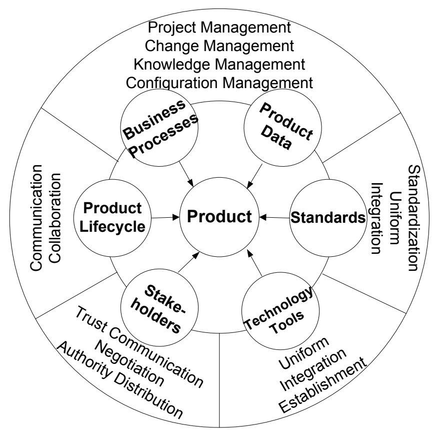

Figure 10 PLM Wheel Model

There are six parts implied in the PLM wheel model: Product Lifecycle; Product Data; Standards; Business Processes; Technology Tools; and Stakeholders. This wheel model classifies and summaries the types of conflicts that may appear in the PLM, and supplies corresponding solutions for each type of conflicts. The product lifecycle level (C1S1, C2S2) refers to the conflicts appearing in the product development phase, production phase, distribution phase, operation phase and retirement phase. Product data level (C3S3, C4S4) represents conflicts about data format, sharing mechanism, technology standards, information semantics, product parameters and product related knowledge in PLM. There are many standards in the stages of the product lifecycle, the origin, the scope and the development process (Nyere). In the standards level (C5S5, C6S6) includes all the problems about standards. Business process level (C7S7, C8S8) represents all conflicts about product market strategy, product portfolio planning, product platform planning, customer requirements, product specification, conceptual design, detailed design, design analysis, prototyping and testing, process planning, inventory management, sourcing production, inspection, packing, distribution, operation and service, disposal and recycle (Association, ; Wu, Yeh et al., 2007). Technology tools level (C9S9) includes conflicts in the technology tool applications. Stakeholders' level (C10S10, C11S11) contains problems in different participants, such as diverse competitive goals among different partners and the inconsistent strategies among different participants.

The collaboration in product lifecycle phase and information sharing mechanism in product data phase can be supported by communication, collaboration, sharing mechanism and project management. Business processes phase is operated through the functionalities such as data management, change management, configuration management, document management, and knowledge management and so on, while standards phase works well based on standardization, uniform and integration. Trust communication, negotiation and authority distribution are the core strategies to solve the problems between different participants in stakeholder phase. As well as the tools' uniform, integration and establishment enhance the efficiency in technology tools phase.

Once we get the product centered model, the refinement for wheel model can be constructed based on Figure 11.

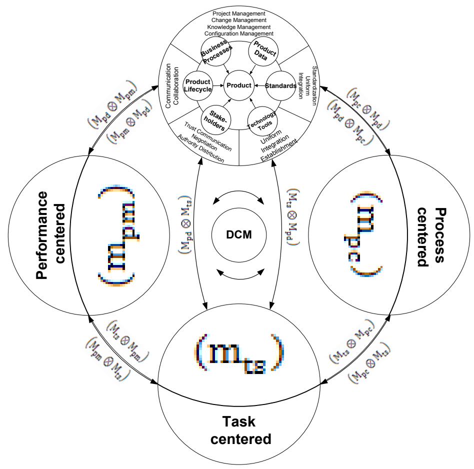

Figure 11 Development for Conceptual Model of DCM

From the example above, it is clear how to get the process centred model, the task centred model and the performance centred model by using EBD methodology. Therefore, the whole wheel model can be completed when these three models are generated.

4.5 Example

In this section, protection of confidential information in design chain management is chosen and addressed for an industrial product, in order to show that the proposed conceptual model of design chain management can clarify and resolve unresolved conflict effectively.

4.5.1 Background

In this part, a real industrial product - Compressed Natural Gas Dryer (Geng and Li, 2008) is studied. It is a dual tower heat – reactivated equipment for natural gas dry procedure, whose primary function is to provide dry natural gas.

Firstly, it is necessary to explain why we are concerned about the confidential information protection for this product. Generally speaking, natural gas must be dried before it can be put into use. The Compressed Natural Gas Dryer introduced in this section has been the major product of a company ABC, which owns a big share of the market. Company ABC's competitors have always wanted to obtain the key technical parameters of the dryer for their own product development. One way they have tried is to go through company ABC's suppliers and customers, in an attempt to reverse engineer the dryer. One of the company ABC's earlier dryer was copied by one of its competitors successfully. In order to avoid the leakage of the key technical information of their newly upgraded product, the company adopted the methodology similar to what we have derived below.

4.5.2 Solutions from the Presented Formalization Approach

According to the analysis based on conceptual model of DCM given in Equation (16), Figure 8 and Table 7, there exists a conflict between developers and suppliers regarding the access to the confidential information held by the suppliers. This is shown in Figure 12. It is hard to make a decision for developers about what design parameters can be safely shared with their suppliers. On the one hand, suppliers need design parameters to supply proper assembly parts. On the other hand, developers want to protect product data for legal and/or competition purposes.

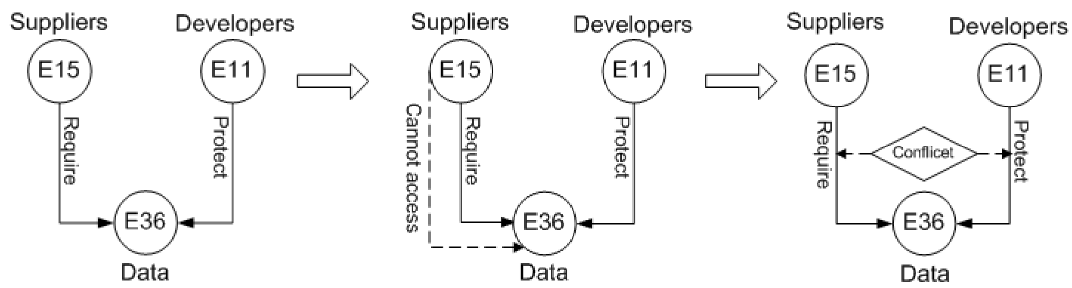

Figure 12 Conflict between Developers and Suppliers

This conflict can be mathematically represented as

$$C\ [\text{require}\ (E_{15}, E_{36}), \text{protect}\ (E_{11}, E_{36})], \tag{17}$$

where $\text{require}(E_{15}, E_{36})$, shows the relationship "require" from suppliers E_{15} to product parameters E_{36} whereas protect (E_{11}, E_{36}) shows the relationship "protect" between developers E_{11} and product parameters E_{36}.

According to the conceptual model of DCM, collaboration and sharing mechanism will be used to show how the conflict in Equation (17) can be resolved. For the conflict (S4) between developers and suppliers mentioned in Section 4.4, available solutions have to be designed and performed until suppliers can access the required data.

The first candidate solution would be to merge developers E_{11} and suppliers E_{15} into a new object E_{11}^*.

$$E_{11}^* = E_{11} \oplus E_{15} = E_{11} \cup E_{15} \cup (E_{11} \otimes E_{15}) \cup (E_{15} \otimes E_{11}). \tag{18}$$

The interaction $(E_{11} \otimes E_{15}) \cup (E_{15} \otimes E_{11})$ can be a collaboration relationship established based on a confidentiality agreement between the developers E_{11} and suppliers E_{15}, shown as $\text{collaborate}(E_{11}, E_{15})$. As a result, the solution can be represented as $C\ [\text{require}\ (E_{11}, E_{36}), \text{protect}(E_{15}, E_{36})] \rightarrow E_{11}^*$. (19)

The second candidate solution (Zhang *et al.*, 2010) would be to divide the object E_{36} such that

$$E_{36} = E_{36}^1 \oplus E_{36}^2 = E_{36}^1 \cup E_{36}^2 \cup (E_{36}^1 \otimes E_{36}^2) \cup (E_{36}^2 \otimes E_{36}^1). \quad (20)$$

In this decomposition, the suppliers would be able to access the parameter E_{36}^1 necessary for their work while the developers will protect their data e_4^2. The key becomes how to devise a reliable interaction mechanism$(E_{36}^1 \otimes E_{36}^2) \cup (E_{36}^2 \otimes E_{36}^1)$. As a result, the solution can be represented as

$$C\,[\text{require}\,(E_{11}, E_{36}), \text{protect}(E_{15}, E_{36})] \rightarrow E_{36}^1 \oplus E_{36}^2. \quad (21)$$

The solutions can be chosen based on different situations. It is better to divide the data into two irrelative parts, so developers can protect what they try to keep confidential and suppliers can get what they want. However, if the data cannot be divided, a confidentiality agreement between the developers and suppliers can be established, which can largely reduce the information leakage risk level.

4.5.3 Confidential Information Protection Technique

Since the most important confidential information is included in the regeneration process, the confidential information risk analysis will be only focused on this process. The paramers to be protected are listed in the priority of protection level.

Parameter T1 plays a key role for the generation process. It is regarded as the top level parameters for confidential protection. The recovering T1 process is shown in Figure 13.

Table 9 Priority of Protection Level

Priority of Protection Level		
Top Level	Process Parameters	Pressure
		Flow Rate
		Temperature
	Empirical Coefficient	Used for engineering design
Moderate Level	Mechanical Parameters	Product model for purchasing parts of equipments

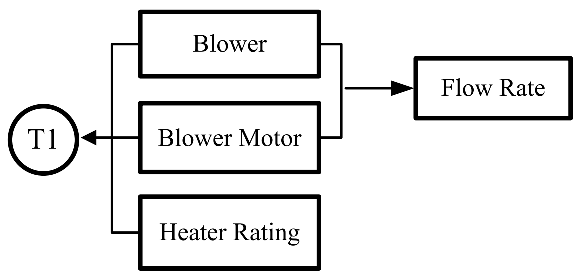

Figure 13 Recovering T1 Process

If one supplier is designed to provide all these three equipments (blower, motor and heater), the risk level of information leakage would be very high. According to the previous analysis, there are two solutions. One is that company makes a collaboration relationship established based on a confidentiality agreement; however, since parameter T1 plays a key role for the generation process, a more stable solution should be considered. The principle of extraction will be applied in this case. Instead of one supplier provides all three parts, the heater, blower and blower motor should be split into small assembly parts and respectively distributed to independent suppliers, the risk level is getting lower. The company can divide these important equipments into small pieces and manufacture the core parts themselves, so it is hard for competitors to know what the original equipments exact are.

The following diagram describes the methodology used for increasing complexity for spy work assumptions. The key is to break the relationships between products or within one part, which leads to less probability for tracing parameters.

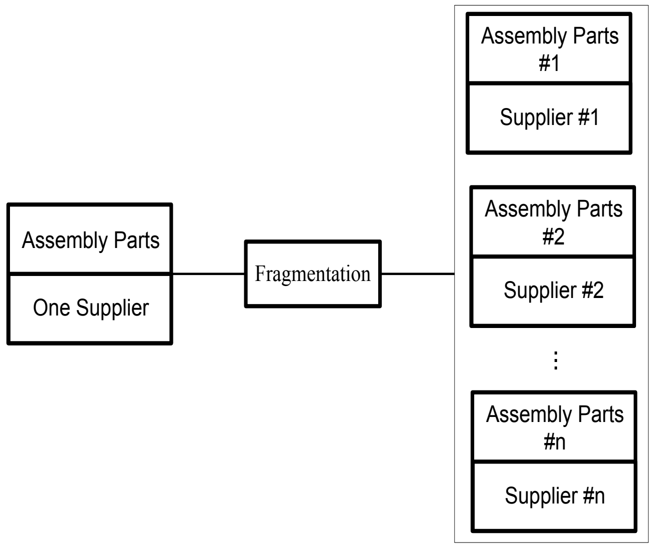

Figure 14 Conceptual DCM Model 1

The details of the techniques are given in (Zhang *et al.*, 2010; Zhang *et al.*, 2010).

4.6 Conclusion

In formalizing design chain management, by using Environment-Based Design (EBD), the formalization process turns an informal definition of design chain management into a formal conceptual model. The conceptual model, which is called a wheel model, is derived mathematically following logical procedures. This formalization approach provides a powerful alternative to the conventional ad-hoc experience based modeling for the development of conceptual model of an engineering process.

Design chain involves various complex components and relationships that present considerable challenges for DCM. The DCM conceptual model generated based on EBD consists of four models: a task centred model, a process centred model, a product centred model and a performance centred model. These interactively related four models constitute the foundation of the design chain management. The product centred model has been further refined as the PLM wheel model. All those four models are wheel models at different levels.

The formalization approach is employed to further formalize a portion of the product centred DCM conceptual model – secure collaboration. The resulted two solutions fit in well with our intuition about the secure collaboration process. The mechanism is implemented in a real industrial case study.

Chapter 5 **Development of Quality Management System**

5.1 Introduction

City of Edmonton, Alberta, Canada runs a monitoring program to monitor and report the performance of the city's drainage system (Edmonton 2004). Under the obligation of ISO 9001and ISO 14001, the city's monitoring group (the customer, hereafter) has decided to develop and implement a quality management manual to provide higher quality and more efficient services with current available resources.

In the beginning of the project, the university research team were not sure about what the customer exactly want and what should be included in the final manual. The sample quality manuals provided by the customer all have different contents. After having failed to satisfy the customer by a manual generated through following a traditional quality management approach, the university research team adopted the EBD methodology by viewing the development of quality manual as a design problem. In conducting environment analysis, a great amount of documents from the customer are organized and digested for the design purpose. Other necessary information is solicited through questions generated by the EBD questioning algorithms. Conflicts in the existing environment monitoring system are identified based on the information such as the characteristics of the drainage system and the ongoing business processes. Solutions are then produced to resolve the conflicts. This process clarified the question what must be included in the quality manual and what must be implemented to enhance the existing environment monitoring process. The customer is finally satisfied with the project results.

The objective of this design problem can be summarized as follows:

> *"*Develop a quality manual for current monitoring system to meet quality requirements and to provide efficient services*"*

5.2 Monitoring System Development

5.2.1 Environment Analysis

The ROM diagram of this objective is drawn as in Figure 15. According to the ROM diagram, it is clear that the component "manual" has the most undefined constraint relations. That means "manual" is the most important component. Based on the question asking strategy mentioned before, the generic questions about objects constraining the critical component "manual" should be further defined firstly. So questions about compound objects "monitoring system", "quality requirements", "efficient service" and "quality manual" should be asked now. For example, we start with object "quality requirements", asking generic questions and answer them: "what kinds of quality requirements should be met?" The answer is ISO 9001 and ISO 24511. Then, we ask questions about ISO 9001 and ISO 24511: "What is the related information in ISO24511?" "What are the requirements based on ISO 9001?" The ROM diagram can be extended based on the answers of these questions.

After finishing question asking for environment components, we should ask questions about the relation objects: "meet" and "provide". We take "meet" as an example, question like "how to meet" can be asked. To answer this question, the content of quality requirements should be analyzed. ISO 9001 asks the scope, the procedure and the interaction of QMS; ISO 24511 requires defining the proper sequence of activities and clear operation instructions. In our case, defining proper sequence and giving clear instruction are the key points to meet quality requirements. Table 10 shows all generic questions, specific question and answers of these questions.

Complying with the product requirements classification roadmap in Figure 4, the specific questions about product lifecycle can be generated. Since the quality manual is specialized for the monitoring group, the product life cycle of our manual includes four stages: design, transportation, use and maintenance. For each stage, the related requirements and components are further classified into built environment, human environment and natural environment. And then, relations between these components are analyzed. The details are shown in Table 11.

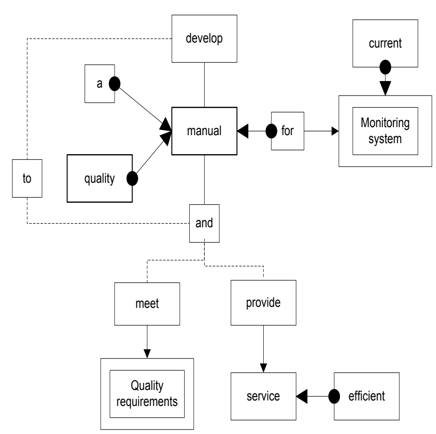

Figure 15 ROM of Requirement Description

Based on the analysis carried out so far, the ROM diagram can be updated as shown in Figure 16. This new ROM diagram gives a clear whole map of the quality management manual for monitoring group. It shows the objective of this manual - giving operation instructions and defining the sequence of operations that involves different components such as people, devices and information system as well as monitoring activities, in order to ensure individual performance and adhere to practice or quality requirements.

Table 10 Generic and Specific Questions

Generic Question	Answer
What kinds of quality standards should be met?	ISO 24511, ISO 9001 …
What is the related information in ISO24511?	"The wastewater utility should define the sequence of all essential operations required for the proper performance of its tasks, processes and activities… More detailed working instructions (such as standard operating procedures and operation and maintenance manuals) should be prepared whenever required, in order to ensure the proper and expert handling of individual activities, adhering to applicable national or generally accepted requirements or practices" (ISO24511, 2008).
What are the requirements based on ISO 9001?	According ISO 9001, a quality manual should include the scope of the quality management system, including details of and justification for any exclusions; the documented procedures established for the quality management system, or reference to them; and a description of the interaction between the processes of the quality management system (ISO9001, 2000).
What does efficient mean?	Performing or functioning in the best possible manner with the least waste of time and effort; satisfactory and economical to use.
What are the characteristics of efficient service?	Less time consuming, low cost, low error rate, high data quality…
What is the environmental monitoring program?	The city of XYZ has a drainage monitoring program under the Environmental Monitoring group which consists of performing several processes for the maintenance and monitoring of different parameters of the drainage systems. People install equipments to different sites for meeting customers' monitoring requirements.
What kinds of objects are included in the monitoring system?	People, device, information system, software.
What is the current situation of monitoring system?	There is no quality manual in current monitoring system. The document management is not good. Technologists just follow their own procedure based on experience, some operations are not proper. The software popularization is not good, so most operations depend on human being. It is hard to avoid human error, time consuming and high cost.
How to meet these quality requirements?	According to the quality standards, it is better to define the proper operation sequences of monitoring activities and to give clear instruction of each activity.
How to provide efficient service?	Reduce the operation time, ensure the quality of data …
Specific Question	Answer
What is the lifecycle of our manual?	In our case, the lifecycle of manual includes design, transportation, use, and maintenance.

Table 11 Requirement Classification

Environment / Lifecycle	Built Environment	Human Environment	Natural Environment
Design	quality requirement, cost, time, interface, basic function	designer, consultant	N/A
Transportation	Time, transportation software	N/A	N/A
Use	information system, equipment	technologist, contractor	N/A
Maintenance	warranty time, maintenance activities	designer, technologist	N/A

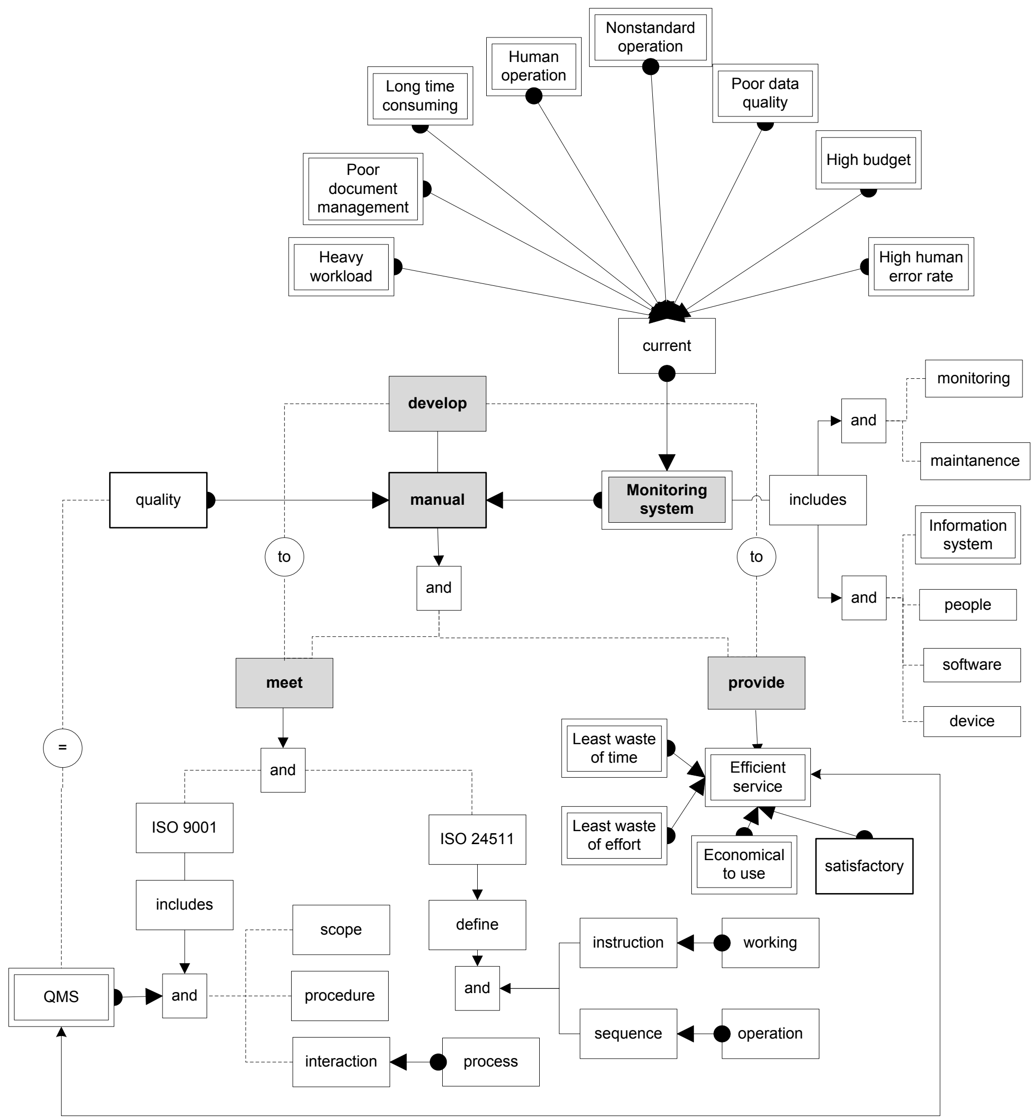

Figure 16 Updated ROM

5.2.2 Conflict Identification

From the environment system which includes objects and their relations, there will be conflicts or potential conflicts between the objects or between their relations. According to Figure 16 , it is obvious that the relations between these environment components are interdependent, which means these are conflicts in current system. Several conflicts are identified based on the relations between environment components shown in Table 12. For example, workload issue exists in current monitoring system; technologists complain that their workload is too heavy. On the other hand, the object of system improvement requests economical using. That means the workload issue should be solved to meet new quality requirements. Since both “heavy workload” and “economical using” constraint “monitoring system”, according to Figure 3, we can get Conflict 3.

Before starting to resolve conflicts, these conflicts should be analyzed firstly. The root conflicts should be identified based on the dependences among conflicts as one conflict can be resulted from others. In such a way, handling a root conflict first may eliminate other depending conflicts. Directed graph is used to represent the relations between conflicts in Figure 17. For example, high human error could increase the operation cost since some operations need double check. Also, human error is an important factor to cause poor data quality. Therefore, high human error can cause high cost and poor data quality, that means c1 can lead to c2 and c7, c1 is the root conflict of c2 and c7. Once c1 is solved, conflicts c2 and c7 will be eliminated correspondingly.

Table 12 Conflicts

#	Significant Conflicts	
c1	High human error rate	Least waste of time; least waste of effort.
c2	High cost	Economical to use; satisfactory.
c3	Heavy workload	Economical to use.
c4	Long time consuming	Least waste of time; least waste of effort.
c5	Poor document management	Least waste of time; least waste of effort; economical to use.
c6	Nonstandard operations	Least waste of time; least waste of effort; economical to use.
c7	Poor data quality	Least waste of time; least waste of effort; economical to use; satisfactory.
c8	Too many human operations	Least waste of time; least waste of effort.
c9	No improve or warranty activities	Economical to use; satisfactory.
c10	No defined efficient sequence of operations	Economical to use; satisfactory.

According to graph theory, adjacency matrix can represent the directed graph with n vertices using an n*n matrix, where the entry at (i, j) is '1' if there is an edge from vertex i to vertex j; otherwise the entry is '0' (Shukla, 2009). Every entry value (i ,n_j) at column n_j shows whether conflict n_j can be represented by conflict c_i. Taking the first column as an example, the value '1' at the 3rd row, 6th row, 8th row, and 10th row means c1 can be lead from c3, c6, c8 and c10. From this table, it is clear that no conflicts can lead to c8, c9 and c10 since the entry values of these columns are all zero, while all the other conflicts can be represented by these three conflicts. Although c5 cannot lead to other conflicts as well as it cannot be represented by other conflicts, which means c5 is also a root conflict. Therefore, c5, c8, c9, c10 are the root conflicts for the monitoring system. Once we solve these four conflicts, the other conflicts will be eliminated or changed.

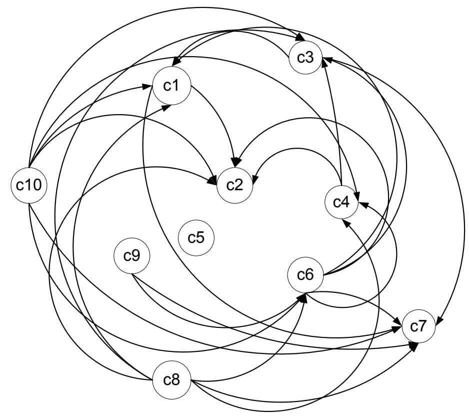

Figure 17 Directed Graph - Dependences among Conflicts

Table 13 is the adjacency matrix that shows the conflict dependency relations in Figure 17. From this table, it is clear that no conflicts can lead to c8, c9 and c10 since the entry values of these columns are all zero, while all the other conflicts can be represented by these three conflicts. Although c5 cannot lead to other conflicts as well as it cannot be represented by other conflicts, which means c5 is also a root conflict. Therefore, c5, c8, c9, c10 are the root conflicts for the monitoring system. Once we solve these four conflicts, the other conflicts will be eliminated or changed.

Table 13 Adjacency Matrix

Conflicts	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10
c1	0	1	0	0	0	0	1	0	0	0
c2	0	0	0	0	0	0	0	0	0	0
c3	1	0	0	0	0	0	1	0	0	0
c4	0	1	1	0	0	0	0	0	0	0
c5	0	0	0	0	0	0	0	0	0	0
c6	1	1	1	1	0	0	1	0	0	0
c7	0	0	0	0	0	0	0	0	0	0
c8	1	1	1	1	0	1	1	0	0	0
c9	0	0	0	0	0	1	1	0	0	0
c10	1	1	1	1	0	1	1	0	0	0

5.2.3 Solution Generation

Based on the previous analysis, it is easy to know what should be included in our manual and what our manual should focus on:

(1) Solving the problems caused by human operation and eliminating the unnecessary human operations;

(2) Defining the efficient sequence of monitoring operations, developing improvement activities and managing documents efficiently.

EBD will be used once again in solution generation stage, in order to analyze the current monitoring system to get the final quality manual.

5.2.4 Environment Analysis for Monitoring System

Monitoring System provides information for assessment and control of existing drainage system performance, as well provides the monitoring report to meet the requirements of City Environment Department and agreements with organizations outside of the city (Edmonton, 2004). It includes many environment components as shown in Figure 16: people, device, information system and software. The detailed information about these components is described in Table 14.

Table 14 Environment Components in Monitoring System

	Component	**Description**
Built Environment	drainage system	The drainage system is responsible for planning, building, operating, and maintaining the pipes, tunnels, pump stations, storm water management facilities that make up the city's drainage network.
	WISIK system	The WISKI Application system is an information system used to monitor and evaluate the effectiveness of city's existing and future sewer systems using accurate and timely monitoring data.
	GIS system	The GIS System can provide site information help select candidate manholes; it also can help identify the potential data quality issues and maintenance cost.
	Equipment	The equipment includes velocity sensors, pipes, bands, probe and meter hooks.
Human Environment	Employee	The field technologists mainly focus on the field practical work and coordinate contractor resources to install, replace and maintain flow monitors; Office technologists issue site installation request, collect site information for requested locations and negotiate with requestors for alternative sites if needed. They also review graphs for problems at the site; circulate graphs for review by senior staff; notify field monitoring staff of site problems; mark incorrect data as bad; store data in database and prepare the final report for customers.
	Contractor	Contractors' work scope include: installing temporary flow monitors; providing maintenance as requested; removing temporary flow monitors; completing two flow monitor verifications; securely fastening flow monitors and sensors; securing the site as required, including the obtaining of permits and allowable times for street/lane closures from Transportation and Streets as needed; and so on.
	Customer	Different customers have different requirements. Some of them need the raw data of drainage system to analyze the performance of sewer system; some of them want to use monitoring data to generate a computer model for data checking; some of them just need the annual report that describe the performance of the drainage system for the whole year.
Natural Environment	Site	The condition of site determines the kind of equipments, the installing location of equipment, and the type of monitoring data and so on.

After analyzing all important components, the relations between these components can be identified in Table 15, where the potential conflicts may exist. Also, this relationship analysis can be helpful to understand the monitoring system clearly for future manual.

Table 15 Relations between Environment Components

Monitoring program		Built				Human			Natural
		Equipment	WISKI System	GIS System	Drainage System	Employee	Customer	Contractor	Site
Built	Equipment		Transfer information through	N/A	Measure	Selected & Used by	N/A	Installed by	Stay in
	WISKI System	Transfer & Save data of		Transfer & Save data of	Transfer & Save data of	Transfer information to	Transfer information to	Transfer information to	N/A
	GIS System	N/A	Transfer information through		N/A	Used by	N/A	N/A	Guide the selection of
	Drainage System	Measured by	Transfer information through	N/A		Monitored by/Working place	Managed by	Working place	Offers
Human	Employee	Select & Use	Transfer information through	Use	Monitor & Work in		Work for	Request	Select
	Customer	N/A	Transfer information through	N/A	Manage	Request		N/A	N/A
	Contractor	Install	Transfer information through	N/A	Work in	Obey	N/A		Work in
Natural	Site	Hold	N/A	Selected based on	Belong to	Selected by	N/A	Working place	

5.2.5 Conflict Identification for Monitoring System

According to the component relation analysis and the operation process analysis, a critical conflict about human operation can be found in data quality assurance and quality control (QA/QC) process. It means that the human operation in QC/QA is the key to solve the conflicts related to human operation. In the current monitoring system, QA/QC are done manually and mostly based on the technologists' experience. On the one hand, the manual checking process overwhelms technologists with heavy workload, thereby introducing human errors and leading to poor data quality; on the other hand, some data problems cannot be identified without comprehensive data analysis. Therefore, if some other technology can be used to replace human operation and to eliminate unnecessary operations in QA/QC process, the problems caused by human operation can be solved and the data quality will be improved.

5.2.6 Solution Generation for Monitoring System

According to the property of conflicts, we try to use computer program instead of human to operate the QA/QC process, the interface is shown as Figure 18. Three algorithms with computer implementations are taken with regard to the quality and efficiency of data assurance. The computer program is implemented by dealing with the following three issues: data rationality and effectiveness check; data drifting check; data sudden change check. There are many advantages by using automatically computer program to instead of human in QA/AC process, such as enhancing quality and accuracy of data assurance, improving the efficiency of data quality assurance and avoiding human errors by relieving technologists of a heavy workload.

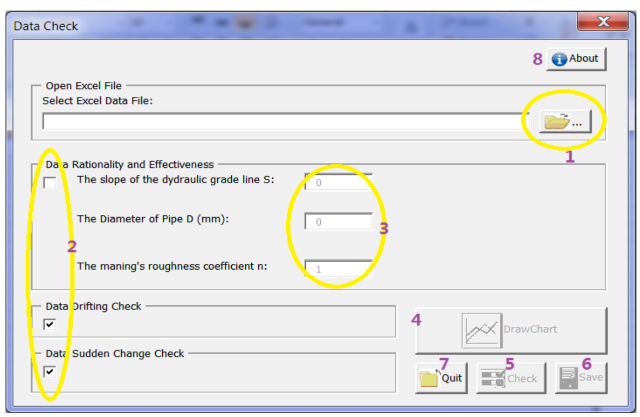

Figure 18 Interface for Data Checking (Liu, 2011)

5.3 Quality Manual for Monitoring System

After checking each monitoring activity and analyzing the relations between these performances, the sequence of activities can be adjusted and redefined in a logical way. Therefore, the correct sequence of all monitoring performance can be generated, which is shown in Figure 19, which can tell the monitoring technologists and contractors what should be done firstly and what should be done after some special activities. It helps construct the standard operation and ensure the effectiveness and efficiency of monitoring operation.

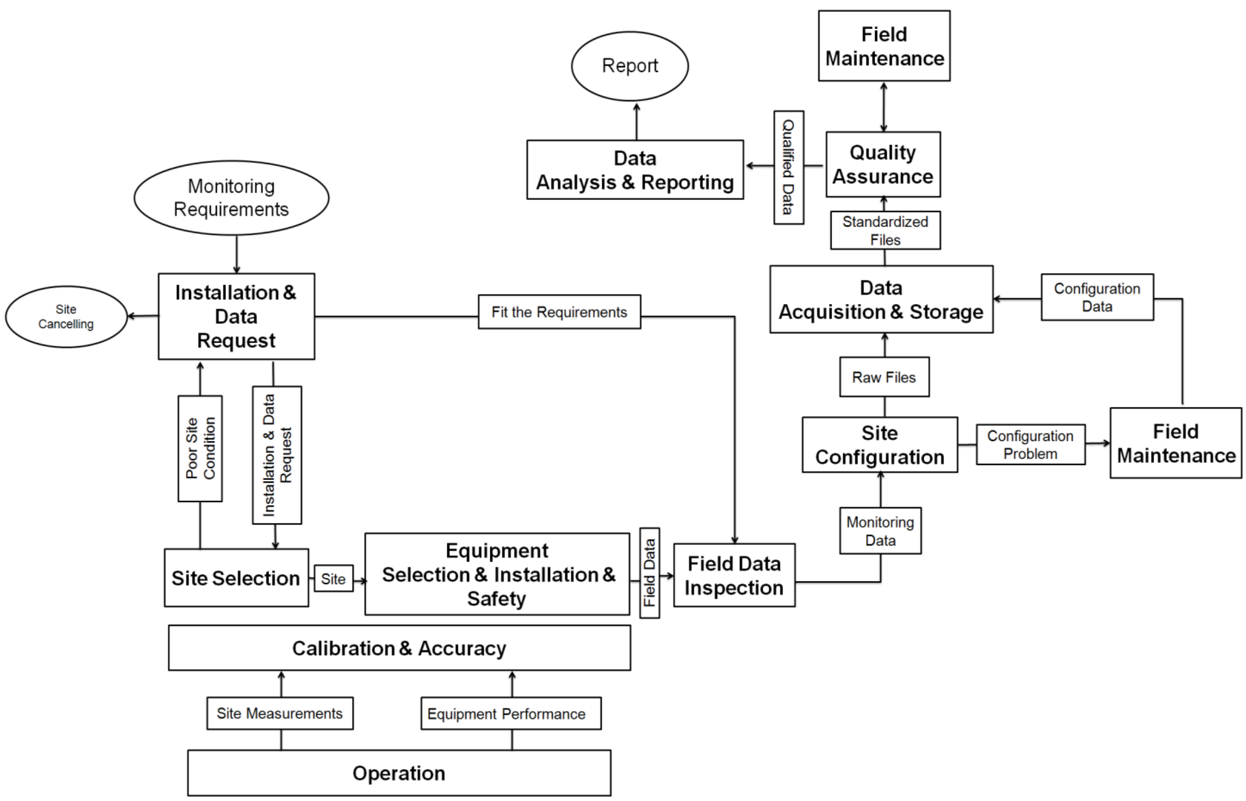

Figure 19 Sequence of Monitoring Activities (Sun, Feng et al., 2010)

The quality standards indicate the opportunities and requirements for improving the monitoring system. According to the understanding of ISO standards, Total Quality Management (TQM), and other related quality methodologies, a template of ideal quality requirements for a quality management system can be generated. Since now we already have the correct sequence of working activities, in order to ensure individual performance and adhere to practice or quality requirements, the ideal template (Sun, Feng et al., 2010) of quality requirements can help us perfect the quality manual. On one hand, the current operation state can be compared with the quality requirements to improve the operation instructions. On the other hand, in our quality manual, proper items from the quality requirement template can be chosen and be followed. This can make sure our manual not only meets the quality requirements, but also has enough information to support the operation instruction.

Table 16 gives an example to show the main contents in our quality manual. All monitoring performances have the same standard documents control process. However, other instructions are different based on their special characteristics. The instruction may include operational manual, control of documents, quality record, quality audit, control of non-conformance, corrective and preventive action, and continuous improvement.

Table 16 Sample Manual - Manual for Quality Assurance

<table>
<tr><td colspan="3">Activity 10: Quality Assurance</td></tr>
<tr><td colspan="2">Predecessors: Data Acquisition and Storage</td><td>Successors: Data Analysis and Reporting</td></tr>
<tr><td rowspan="8">Operational Manual</td><td colspan="2">1. Check the data</td></tr>
<tr><td colspan="2">2. Draw the graphs</td></tr>
<tr><td colspan="2">3. Review graphs for problems at sites</td></tr>
<tr><td colspan="2">4. Circulate graphs for review by sensor staff</td></tr>
<tr><td colspan="2">5. Notify field monitoring staff of site problem</td></tr>
<tr><td colspan="2">6. Mark incorrect data as bad</td></tr>
<tr><td colspan="2">7.Store data in database</td></tr>
<tr><td colspan="2">8. Data repairing and finalization</td></tr>
<tr><td rowspan="4">Quality Audit</td><td>Audit duration</td><td>one day to three days</td></tr>
<tr><td>Audit procedure</td><td>check and record each procedure</td></tr>
<tr><td>Audit people</td><td>Office Work technologists</td></tr>
<tr><td>Audit report</td><td>N/A</td></tr>
<tr><td rowspan="2">Non-conformance and possible actions</td><td colspan="2">QA/QC process depend on technologists' experience</td></tr>
<tr><td colspan="2">Use computer program instead of human to operate the QA/QC process</td></tr>
<tr><td>Continuous Improvement</td><td colspan="2">Since we use computer program to replace human operation in QA/QC process, continuous program debug should be considered.</td></tr>
</table>

5.4 Conclusion

Environment Based Design (EBD) methodology includes three interdependent design activities: environment analysis, conflict identification and solution generation. This paper presents a case study to show how the EBD (Environment-Based-Design) methodology can be applied to real industrial problems.

This case study is from an industrial project, which aims to creating a quality manual that guides the development of quality management systems (QMS)) in an environment monitoring group in a city. Since the required deliverable is not a QMS, the content of the manual was not precisely defined in the beginning. The EBD was adopted to accomplish this task after a failed endeavour following a widely accepted quality management methodology. It was found from this project that the EBD is able to clarify the goals of the project step by step and to guide the project members to follow the right path. The final deliverable turned out to be a quality manual together with a data processing tool, which have addressed the customer's real concerns.

In applying the EBD, the environment analysis activity clarifies the definitions of key components such as manual, drainage system, environment monitoring, and quality standards. Following those definitions, the structure of the manual was determined based on the right sequence of monitoring activities identified through analyzing the main environment components and the relations between these components. The conflict identification activity then finds the incompatibility and inconsistency among the relations implied in the environment system. Finally, the quality manual was developed by resolving a few major conflicts in the current system.

Chapter 6 **Conclusions and Future Work**

6.1 Conclusion

The objective of this thesis is to validate the effectiveness of Environment–Based Design (EBD) as a generic design methodology. EBD methodology is a recursive design methodology, which includes three interdependent design activities: environment analysis, conflict identification and solution generation.

The validation of EBD is conducted based on two case studies. One is the formalization of design chain management (DCM). A formal conceptual model of DCM is generated from its informal definition by applying EBD. In the second case, EBD is adopted to develop a Quality Management System (QMS) and generate a quality manual for an environment monitoring service.

The logical and interpretable formalization process of DCM in the first case shows that EBD is an effective design methodology. By using EBD, the DCM conceptual model is generated step by step. The final DCM model and application example proves that the results developed by using EBD logically use meaningful reliable information and not bias the designer, which meets the requirements of effectiveness validation.

In the second case, the challenge was that the content and structure of the final manual were not clear to the customer. By taking this task as a design problem, EBD helps get the real customer requirements from a fuzzy description and develop the QMS by solving the root conflicts. After critical conflicts were identified, the quality manual and a data processing software were produced for the client. In addition to the conventional conceptual design problems, the EBD is particularly efficient when customers do not know clearly what they want and what the product should look like.

In conclusion, EBD is a logical and recursive process aims providing right direction to designers and support them determine the focus at each design stage (Zeng, 2011). EBD has a good requirements analysis process, which helps analyse the current situation and guide to right direction for information collection. Also, the EBD gives detailed instruction for design, so designers can manage their mental stress and focus on the creative activities. The features of EBD ensure all efforts in design achieve the right goals and requirements, which prove that EBD is an effective as a generic design methodology.

6.2 Future Work

By studying and validating EBD theory, the following work can be continued in the future.

1. More research should be conducted on the theoretical basis for the purpose of fully validating EBD.
2. For the DCM conceptual model, future work will include the refine of the other three DCM conceptual models – process centered model, performance centered model and task centered model.
3. Conflict identification and solution generation activities in EBD should be further defined in future.

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