Preliminary Study of Ontology for Systematic Gathering of Product Requirements

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Abstract

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Industry practice shows that many of the problems in product design arise from a misunderstanding of the requirements or from the existence of ambiguities in the statement of the product requirements or from both. There has been a lack of a robust requirements management system to help designers to get the right requirements in the right time. The main objective of this thesis is to develop ontology for systematic gathering of product requirements.

The starting point of this thesis is the environment-based design theory by Zeng (Zeng, 2004), where product requirements are attributed to the conflicts in product environment. This present thesis extends the environment-based design theory in two aspects: first, ontology is developed for product environments based on product life cycle; secondly, ontology for product-environment relations is investigated from the perspective of traditional engineering sciences. By using these two sets of ontology, product requirements are classified into three levels: product, corporate, and environment. Based on the ontology and taxonomy developed in this thesis, systematic procedures are proposed to gather product requirements. A case study is used to demonstrate how this research can be applied to develop right product requirements for the product design.

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Chapter 1 **Introduction**

1.1 Motivation

The correct specification of product requirements is the first step in achieving a quality design. The design process begins with identifying the requirements. One establishes these requirements for the intended product by beginning the design process with the recognition of a need. As John von Neumann has said, "There's no sense being exact about something if you do not even know what you're talking about."(Gause, 1989). Hence, a design starts with understanding the customer's needs and requirements.

Industry practice shows that many of the problems in product design arise from a misunderstanding of the requirements or from the existence of ambiguities in the statement of the requirements. Sometimes, when customers talk to designers about their expected product, they may not know what their real requirements are; moreover, they do not fully appreciate what it is that would best suit them. For example, if a customer requests to have the design for a portable cleaner that can clean the floor easily, he or she has used imprecise language. Does "portable" mean "moveable along the ground" or does it mean "moveable by hand"? Clearly the customers do not appreciate that what they are saying is not clear. The two different meanings would lead to different solutions. In many cases, customers use the words such as "easily" or "safely". What is the real meaning of these words? If you want to identify them, you have to understand the relationships between customers and product.

There has been a lack of a robust requirements management system to help designers to get the right requirements from multiple sources even though there are several techniques for this purpose.

Quality Function Deployment (QFD), also known as The House of Quality (HOQ), is one popular technique to identify customer's requirements and the relationship between customer's requirements and technical specifications (Yoji Akao and Shigeru Mizuno, 1965). QFD is designed to allow customer input throughout the design, production, marketing, and delivery facets of a given product or service. In a typical QFD application, a cross-functional team creates and analyzes a matrix linking customer wants and needs to a set of product and service design metrics that the company can then measure and control. However, in QFD, the requirements typically refer only to consumers' or end-users' requirements. Actually, it is necessary to consider all customers from the beginning of the design process, not just end users. The members of marketing, manufacturing, and maintenance should be considered as customers, too.

In 1994, Stauffer and Morries discussed a taxonomy that includes lifecycle design considerations in a product design (Stauffer and Morries, 1994). Although they suggest the use of such taxonomy for product requirements, they do not develop it in detail.

In 2004, Dr. Yong Zeng develops an environment-based formulation of design problem (Zeng, 2004). In this theory, he addresses that all the product requirements in a design problem are imposed by the product environment in which the product is expected to work and the requirements are derived from the relations between the product and its environments. However, he did not classify environment components in the every stages of product life cycle, and he did not classify the relations between the product and its environments.

Hence, a systematic model for developing product requirements is essential. In this thesis, the author aims to develop a systematic procedure for gathering product requirements by extending the environment-based design theory (Zeng, 2004) in two aspects:

- Develop ontology for product environment based on the product life cycle
- Develop ontology for product-environment relations

Ontology is an explicit formal specification of how to represent the objects, concepts, and other entities that exist in some area of interest and the relationships that hold among them. The subject of ontology is the study of the categories of things that exist or may exist in some domain (Sowa, 2000). By studying traditional engineering, the author develops the two sets of ontology and a taxonomy for product requirements. They help designers identify the environment components, identify the relations between a product and its environments as well as classify the requirements.

1.2 Challenges in requirements management

Basically, there are three major challenges in the management of customer requirements. First, since the information about requirements is so broad and complex, it is sometimes not easy to capture all requirements. The second challenge to designers is how to put the comprehensive requirements into a well-defined structure. The third challenge for designers arises from how to start to gather the information about the requirements.

As the complexity of the design problem has become more evident, the information in requirements is becoming broader and more complex. First, requirements are becoming multiplex. Briefly, the requirements of a product can be broadly classified as engineering, economic, ergonomic, legal, environmental, and other. At the beginning of a design project, what a designer can get from customers is just basic functional requirements of a product. However, for a completed design, the designer needs to consider not only the functions that can meet customers requirements but also the cost requirements of the product, the time requirements of producing as well as requirements of the competitiveness in marketing. Moreover, identifying the requirements is complex because of the interaction and the conflict between the requirements themselves. For example, environmental requirements would call for non-polluting manufacturing process, which conflicts with economic requirements because it requires more investment in waste treatment. Therefore, the multiplex of requirements results in the challenge presented by gathering requirements. Second, before each type of requirements is dealt with in detail, it should be pointed out that the requirements for each type should be rooted in the many sources in a product life cycle. For example, engineering requirements pertain not only to manufacturing stage but also to the usage stage of the product. When we consider the ergonomic requirements, we should take into account all the human beings who participate in the product life cycle, such as customers, end-users, maintenance technicians, sellers, and so on. In the recent years, the program called

Design for X (X stands for the manufacturing, assembly, environment, market and so on) is considered as a systematic design methodology (Dixon and Poli, 1995). The essence of this methodology is to consider all the requirements in the different stages of the product life cycle in the design although the emphases are distinguished for different purposes. Hence, how to gather integral and comprehensive requirements is a challenge to designers.

In addition, since the information about requirements is complex and multiplex, how to organize the requirements and put them into a structured format is a problem for a designer. For example, based on manufacturing requirements, a product requires material that has good feature of machining. At the same time, environmental standards require non- Polluting material. The two requirements concern the limitations put upon the materials. We can put the requirements of materials into the material category, and we can put each of them into manufacturing category and environmental category, respectively.

Another challenging job for a designer is how to start gathering requirements at the beginning of a design project. There are dozens of studies that present the methodologies helping designers to process the gathering of information about the requirements. QFD is a well-known method of collecting customer's requirements (Yoji Akao and Shigeru Mizuno, 1965); LCA (Life Cycle Assessment) is an integrated "Cradle to grave" approach to assess the environmental performance of products and services, especially in the requirements of raw materials selection and the impaction to environment (LeVan, 1995). DfE (Design for Environment) is another systematic integration of environmental considerations into product and process design. It focuses on the requirements related to the environment. LCCA (Life Cycle Cost Analysis) is an economic evaluation technique that determines the total cost of owning and operating a facility over a period of time (Juneau, 1999). This method focuses on economic factors such as cost and revenue factors in a design. Since all the requirements are essential, the problem faced to designers is how to start to process the gathering of requirements. It is essential to decide if it should start from functional requirements, or from environmental requirements, or from others? Many designers, especially some experienced designers are easy to jump into functional requirements that are arisen from customers directly. However, they may ignore many requirements from the other sources, such as from law and regulation, from environment, and from human factors, which are necessary to a product, too. Hence, a template of a systematic requirements analysis approach is necessary to be developed to help designers to start the process of gathering requirements.

1.3 Research objectives

In this thesis, the author aims to develop an approach that will help designers to gather and manage the requirements by extending the environment-based design theory (Zeng, 2004). Therefore, the objectives of this thesis are the following:

- Develop ontology for product environment components based on product life cycle by using the environment-based design theory

According to the environment-based design theory, the requirements are the relationships between the product and environments in which the product is expected to work. The first step, which consists of identifying the requirements, is to clarify the environments at each stage of the product life cycle.

- Develop ontology for product-environment relations between a product and its environments

Basically, the key to identifying requirements is to identify the relationships between the product and its environments.

- Develop a taxonomy for product requirements

Taxonomy is a good method for organizing the large bodies of information (Stauffer and Morries, 1994), especially in the classification of the design requirements in product life cycle. For a product design, a well-defined taxonomy is used by designers to classify the requirements. Such a taxonomy is easy to understand.

- Develop a systematic procedure for gathering product requirements

The process of gathering requirements is a systematic job for a designer. As the complexity of product increases, so do the requirements of a product design. Developing a model or procedure to help designers gather and analyze the requirements is one of the objectives of the present thesis.

1.4 Deliverables

The author aims to provide the following deliverables in the requirements management of a product design:

- An ontology for product environment components

It is useful for designers that they can know which factors should be considered in the product life cycle and where those factors from.

- An ontology for product-environment relations

This ontology helps designers understand the relationships between the product and its environments.

- A taxonomy of requirements classification

This taxonomy allows for an organized method of gathering, managing, and retrieving the requirements. Moreover, the taxonomy can provide a template to create taxonomies for a product with a company or an industry.

- A systematic procedure for gathering product requirements

The procedure helps designers know how to gather the product requirements and how to start.

1.5 Thesis structure

The structure of the remainder of this thesis is explained in Figure 1.

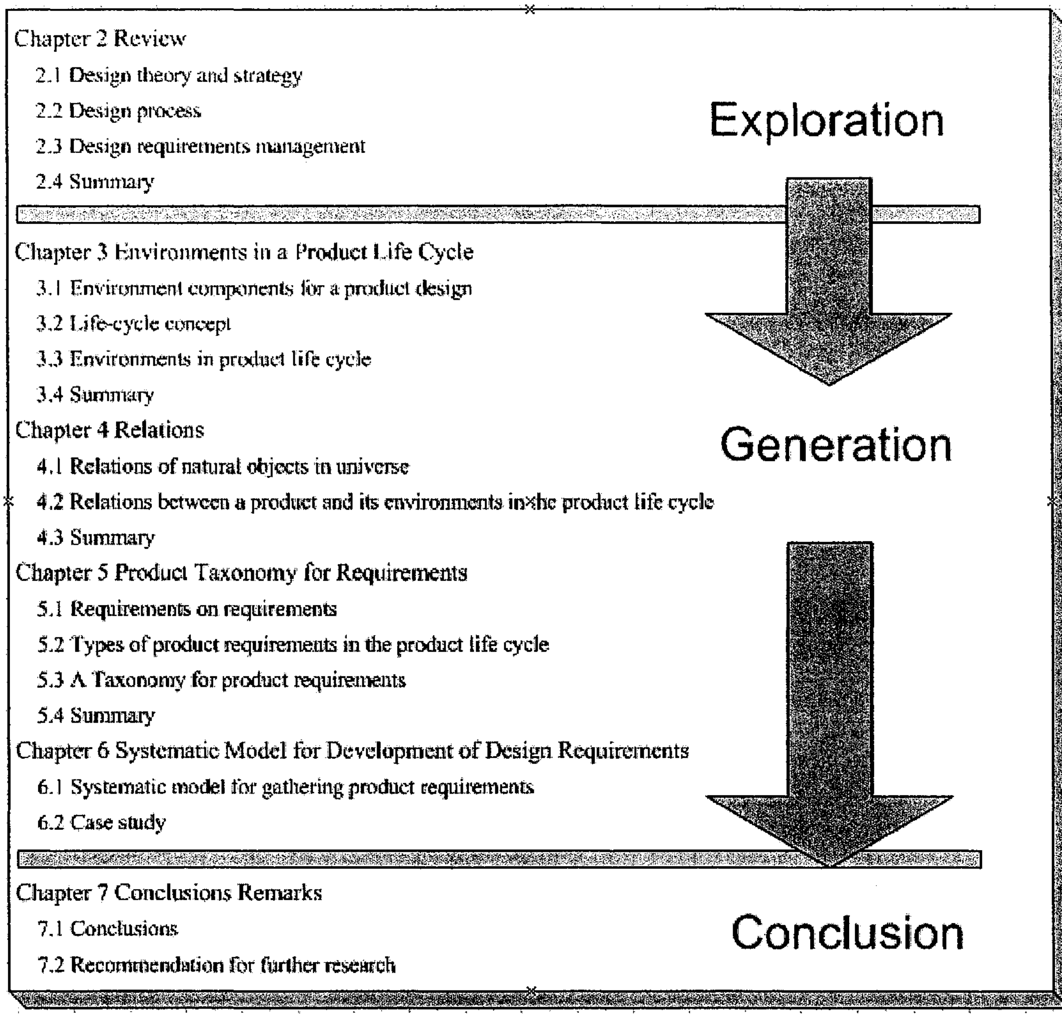


Figure 1: Structure of the thesis

The three phases of the thesis are as follows:

- The exploration phase of the thesis introduces the strategy and theory of the design process and reviews the achievements of the other researchers in requirements management. The fundamental theory applied in the thesis, environment-based design theory, is also introduced in this part.
- In the generation phase of this thesis, the environments in the product life cycle are identified first. The relationships between the objects in nature are discussed and the

requirements are extracted according to the relationships between the environments and the product. Finally, environment-based requirements taxonomy is developed to organize the requirements.

- In the conclusion of the present thesis, the final conclusions and recommendations for future research are made.

Chapter 2 Review

In this chapter, the author aims to review the related work and summarize other researchers' achievements. First, the design strategy and design process that are used broadly in the product design are reviewed. Secondly, the author summarizes the other researchers' work and achievements in requirements management of a design. The axiomatic theory of design modelling as well as its extension- environment-based design theory, which is the fundamental theory used in the present thesis, is also reviewed in this chapter too.

2.1 Design theory and strategy

Since the start of the industrial revolution, science and technology have reached an amazing level at an ever-accelerating rate. From the spacecrafts and computer system, humans have achieved a lot in the product design. Despite these and other brilliant achievements, we are still surrounded by many technological and societal problems that have been created through poor design practices. In order to obtain a good design, many researchers and organizations are developing and promoting best design practices.

In the engineering design domain, two strategies are widely used: bottom-up and top-down strategies.

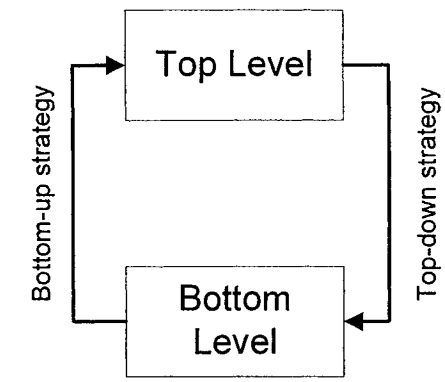


Figure 2: Bottom-up and top-down strategies

2.1.1 Bottom-up strategy

A bottom-up strategy assumes one designs a system from the individual evidence bottom-level systems up through the top-level system. If the design is constrained by low-level functionality, you can build that low-level functionality first to get an idea of how it will be used. For example, if one wants to design a machine, one can choose a machine that has already been created. One can then add extra attributes and functionalities that the user requires. This is the bottom-up strategy. With this strategy, the design objective is to select an old design containing information similar to the lower-level requirements.

The bottom-up design works best when one has past designs that are representative of many features that contain similar functions. When the bottom-up design strategy is used, one can start with past designs that contain a good representative sample of functions and features to be designed. Then the design can be successively reached to higher level. Therefore, this approach is also useful when a design is not required for many changes or additions compared with the old design. However, the problem with the bottom-up design is that, because you do not start with a clear idea of the big picture, you may build pieces that do not fit together correctly. Therefore, the bottom-up strategy is most effective in the design of used parts in a redesign.

2.1.2 Top-down strategy

A top-down strategy assumes that one designs a product from the top-level system down through the individual components. To design by the top-down strategy, one must adopt a taxonomy, or scientific classification approach, to create a system in three levels as follows:

- Top-level system – use general headings to identify the system area
- Sub-system – use more specific headings to identify the primary groupings within the system area, as well as sub-systems that are increasingly more specific.
- Components – define the components by using important terms, acronyms, or jargon.

A top-down design works best when requirements are clearly defined. This approach is also ideal if the product is under constant growth or change. With this strategy, it is likely that a new product may be designed.

Basically, the top-down strategy of design has following characteristics (Dijkstra, 1969) and (Wirth, 1971):

- The design activity must begin with the analysis of the requirements definition and should not consider implementation details at first.

- A project is decomposed into subprojects, and this procedure is repeated until the subtasks have become so simple that an algorithm can be formulated as a solution.

The top-down design is a successive concretization of abstractly described ideas for a solution. Abstraction proves to be the best medium to render complex systems comprehensible; the designer is involved only with those aspects of the systems that are necessary for understanding before the next step or during the search for a solution.

Therefore, top-down design follows the true design process more closely, especially in conceptual design.

2.2 Design process

Definitely, design is a process by which the needs of the customer or the marketplace are transformed into a product satisfying these needs. Design theories address the nature and models of the design process, of design objects, and of design knowledge. It can be applied to improve the design process.

Eekels proposes that researchers studying in design methodology not only aim at understanding the phenomena of design, but also use their understanding in order to change the way the design process is carried out (Eekels, 2000). It is usually carried out by a designer or an engineer but requires help from other people in the company as well.

Design essentially is an exercise in problem solving. Typically, the design of a new product consists of the following stages (Eekels, 2000):

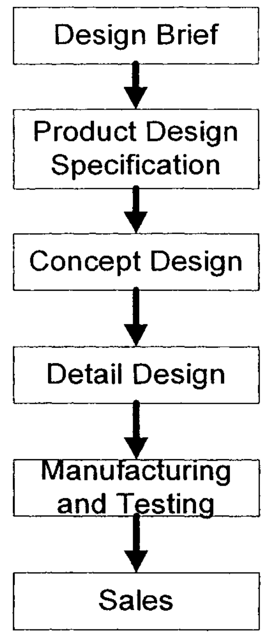


Figure 3: A design process (Eekels, 2000)

From the process presented in Figure 3, we can see that a design project starts from the development of design requirements. The principal aim of the deign brief is to communicate design expectations to the design team. The design brief is not just a static document that is referred to at the beginning of the process. It is referenced throughout the design process to ensure that the solution being developed actually fits the problem. Basically, the major part of the design brief is to identify the problem and clarify the customer's needs. In the other word, developing the requirements is one of the important objectives in the design brief.

The traditional view of the design to manufacture process is that it is a sequential process; the outcome of one stage is passed on to the next stage. However, it is reality that this tends to lead to iteration in the design since a designer has to go back to an earlier stage to correct mistakes when he finds a problem in the process. This can make products more expensive and can delay the delivering to the marketplace. A better approach is for the designer to consider the stages after the design to try and eliminate any potential problems at the beginning. This means that the designer requires help from the other experts in the company for example the manufacturing expert to help ensure that any design the designer comes up with can be made.

The factors that a designer has to consider in order to eliminate iteration are listed as follows:

- **Manufacture** - Can the product be made with our facilities?
- **Sales** - Are we producing a product that the customer wants?
- **Purchasing** - Are the parts specified in stock, or do we have to order them?
- **Cost** - Is the design going to cost too much to make?
- **Transport** - Is the product the right size for the method of transportation?
- **Disposal** - How will the product be disposed at the end of its life?

2.3 Design requirements management

Requirements management is a well-know methodology that has been rapidly adopted by industries. It refers to the activity concerned with the effective control of information related to product and system requirements, the preservation of the integrity of the information during the life of the product and system, and respect concerning changes in the system and its environment. As Ritter said, "You cannot understand the problem without having a concept of the solution in mind, and you cannot gather information meaningfully unless you have understood the problem but you cannot understand the problem without information about it"(Ritter, 1984). Hence, a design process is initiated with the recognition of a need and the establishment of requirements for the intended product (e.g. Pahl and Beitz, 1984). There are a number of studies that have stressed the importance of customer requirements as a source for new product ideas (Logan 1997; Wood 1996). Many studies (Cooper 1987; Davidson 1976; Maidique and Zirger 1985; Bruce and Rodgus 1991; Montoya-weiss and Calantone 1994; Walsh et al. 1992) have found that the factors that distinguish new product success from failure are the consideration and understanding of user requirements.

2.3.1 Requirements management methods

Since identifying the requirements is very important in a design process, many researchers have devoted attention to this problem. Pahl and Beitz (1988) characterized a product specification as being a collection of product requirements. They provided a categorization scheme for product requirements such that every product requirement in a specification belongs to one requirement group, and they provided an abstraction of the design task form the most general demand (the overall requirements) to more specific demands (sub-requirements). Figure 4 shows the idea of how to decompose the requirements and how to make functions correspond with sub-requirements (Kusiak and Szczerbicki, 1992).

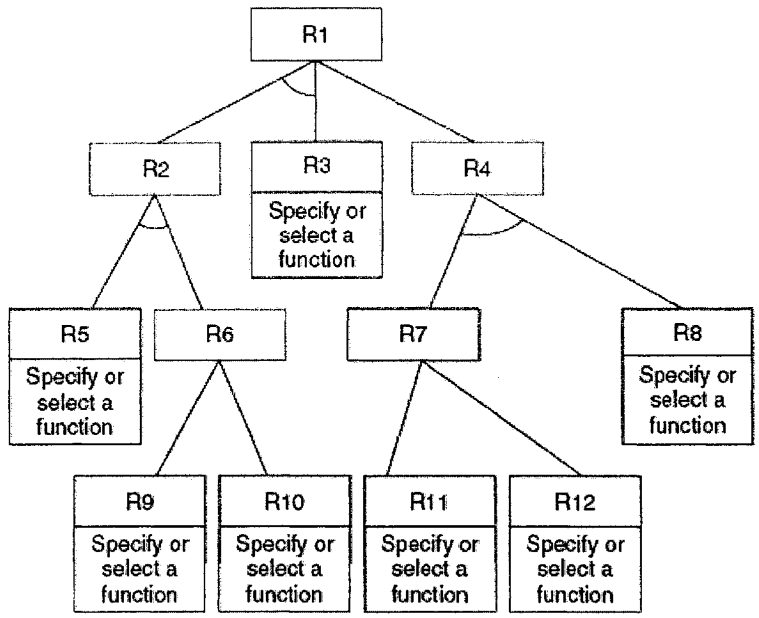


Figure 4: Decomposition of requirements (Kusiak and Szczerbicki, 1992)

Bailetti and Litva (1995) have addressed two ways to derive the customer-related knowledge (K) that the designer uses to evolve the design model. One way is to derive information endorsed by management solely from customer requirements (K_α), and the other way is to derive information produced and used locally (K^*). Figure 5 illustrates the relationship between them.

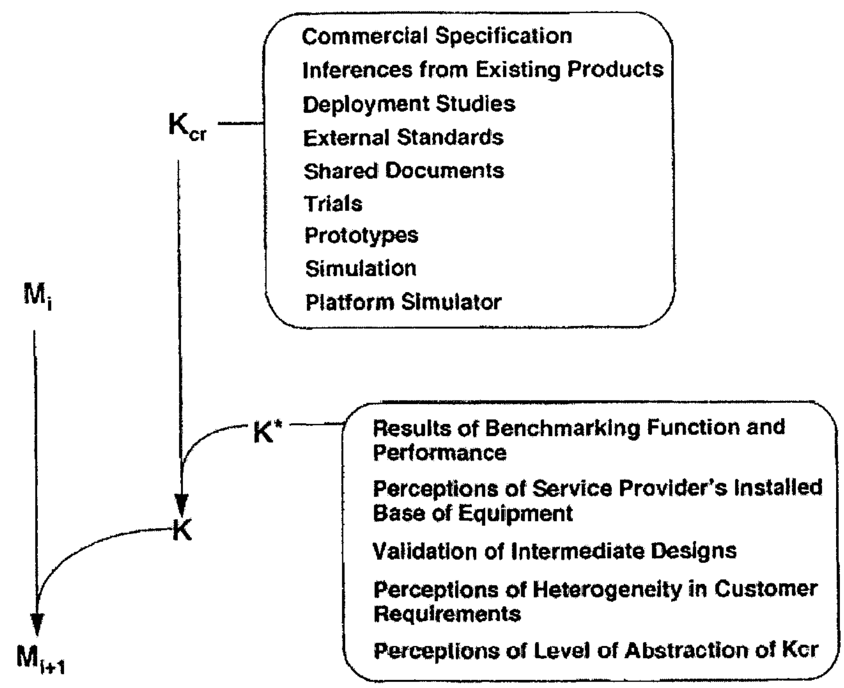


Figure 5: Sources of customer requirement information used by designers to evolve design model (Bailetti and Litva, 1995)

pioneered Quality Function Deployment (QFD) philosophy (Yoji Akao and Shigeru Mizuno, 1965). Although it is not originated as a requirements engineering technique, it is rather used as a technique for requirements engineering borne out of the quality movement to translate customer's requirements into specific product design targets. As Madu said in his book House of Quality in a Minute (1999), "Quality Function Deployment is a process of listening to the 'voice of the customer', identifying the customer's needs, and incorporating those needs in the design and production of goods and services". As a technique of requirements engineering, QFD can be used by designers to gather customer's requirements, prioritize requirements, generate technical requirements, analyze correlations between customer's and technical requirements, and analyze the independence between the technical requirements. The structure of requirements development is illustrated in Figure 6.

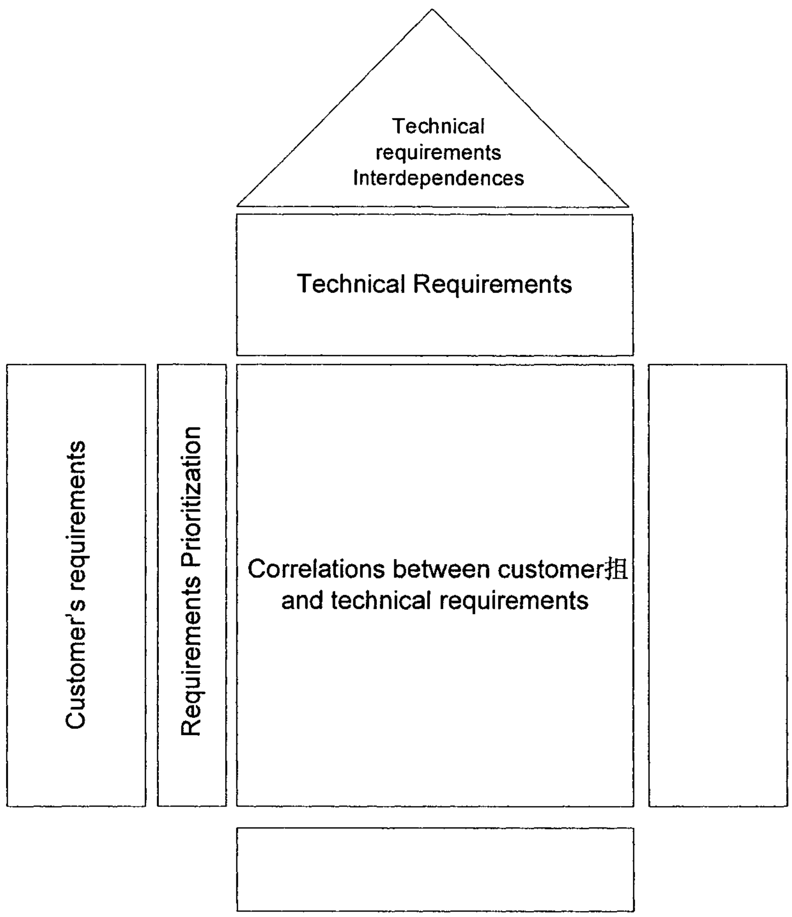


Figure 6: Requirements in QFD (Yoji Akao and Shigeru Mizuno, 1965)

QFD focuses on "Voice of customers"; however, the idea that the customer's voice might not contain "true" requirements but rather approximations to true requirements because customers are rarely effective at stating requirements in enough detail for developers. Moreover, the requirements come from customers is only one part of the requirements for a product design. The other requirements, such as regulation requirements and environmental requirements cannot be captured from customers.

Taxonomies are commonly used to classify large bodies of information. Within the field of a mechanical design, a well-known taxonomy is Ullman's taxonomy of mechanical design (Ullman, 1989). In this taxonomy, Ullman classifies design problem and tools to solve the problem in terms of environment, problem, process, and research approach. However, this taxonomy does not classify product requirements. In 1989, Stauffer and Slaughterbeck-Hyde discuss a taxonomy that includes lifecycle design considerations, and they suggest the use of such a taxonomy for product requirements, but they do not develop it (Stauffer and Morries, 1994). For the purpose of defining product design requirements, Gershenson (1995), Gershenson et al. (1994), Gershenson and Stauffer (1995, 1996, 1999a, 1999b) and Morris and Stauffer (1994) have developed a taxonomy to integrate the consideration of manufacturing and other product issues into the development of design requirements. At the highest level of Gershenson's taxonomy, there are four areas of requirements: end user requirements; regulatory requirements; corporate requirements; and technical requirements. The detail of the four classes of requirements is classified as follows:

- *End-user requirements*: performance characteristics, usability, aesthetics, styling, and safety
- *Regulatory requirements*: safety, health, environment, and product retirement
- *Corporate requirements*: marketing, business environment, strategic management, finance, accounting, and product manufacturing, distribution, support and service, and retirement
- *Technical requirements*: engineering practices (standards, codes), product manufacturing, and resources (material and parts availability)

In contrast to the consumer or an end-user requirement, Stauffer and Gershenson (1999) developed a taxonomy to classify the corporate requirements, which come from internal sources such as finance, manufacturing, and maintenance. They divide the taxa into three levels: the functional level; the task level; and the attribute level.

- *The functional level*: Those requirements taxonomies represent a functional group of the corporate requirements, such as marketing, manufacturing, service, retirement, and so on.
- *The task level*: those requirements contain the tasks that describe what must be done to accomplish the level of lifecycle issue or function.
- *The attribute level:* Those taxonomies are made up of those elements of a product that a designer may specify, such as geometry, feature, tolerance, and so on.

Researchers and designers have recognized the importance and comprehensiveness of requirements development. Although they spend considerable time to capture the needs of customers, there are still some requirements missing or ignored. Therefore, a systematic requirements development problem is necessary for dealing with this problem.

By using axiomatic theory of design modelling (Zeng, 2002), Zeng defines a design problem in environment-based formulation (Zeng, 2004). From the formulation of design problem, he classifies the product requirements into functional and structural. The fundamental theory is reviewed as follow.

[Definition 1] A product system is the structure of an object (Ω) including both a product (S) and its environment (E). It can be denoted as:

$$\Omega = E \cup S, \forall E, S [E \cap S = \Phi], \quad (1)$$

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

Based on the definition of structure operation, the product system (⊕Ω) can then be expanded as follows:

$$\oplus \Omega = \oplus(E \cup S) = (\oplus E) \cup (\oplus S) \cup (E \otimes S) \cup (S \otimes E), \quad (2)$$

where ⊕E and ⊕S are structures of the environment and product, respectively; E⊗S and S⊗E are the interactions between environment and product. A product system can be illustrated in Figure 7:

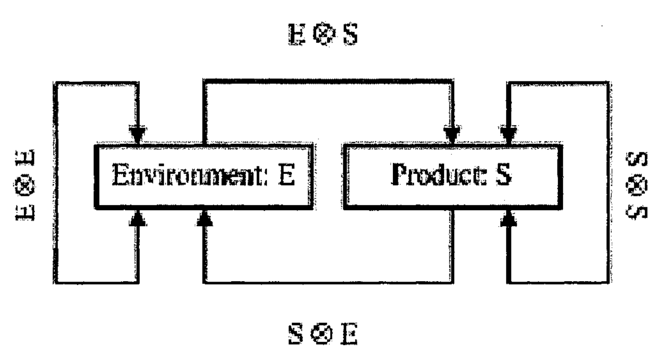


Figure 7: A product system (Zeng, 2004)

[Definition 2] Product boundary, denoted by B, is the collection of interactions between a product and its environment.

$$B = (E \otimes S) \cup (S \otimes E). \quad (3)$$

There are two types of product boundary: structural boundary and physical interactions. The structural boundary (B^s) is the shared physical structure between a product and its environment. The physical interactions include actions (B^a) of the environment on the product and responses (B^r) of the product to its environment. Therefore, product environment boundary can be further represented as:

$$B = B^s \cup B^a \cup B^r, \quad (4)$$
$$\forall B^s, B^a, B^r[(B^s \cap B^a = \Phi) \wedge (B^s \cap B^r = \Phi) \wedge (B^a \cap B^r = \Phi)].$$

Since environment as well as product may have components, structures ⊕E and ⊕S can be further decomposed into the structures of these components as well as their mutual interactions according to the definition of structure operation.

A design problem can be literally defined as a request to design something that meets a set of descriptions of the request. Based on the axiomatic theory of design modeling, both "something" and "descriptions of the request" can be seen as objects and can be further seen as product systems in the context of formulating design problem. Thus a design problem, denoted by P^d, can be formally represented as:

$$P^d = \lambda(\oplus\Omega_0, \oplus\Omega_s), \quad (5)$$

where $\oplus\Omega_0$ ($\Omega_0 = E_0 \cup S_0, E_0 \cap S_0 = \Phi$) can be seen as the descriptions of a request for the design, $\oplus\Omega_s$ ($\Omega_s = E_s \cup S_s, E_s \cap S_s = \Phi$) is something to be designed,

and where :

λ : The "inclusion" relation

$\supseteq$: implying that $\oplus\Omega_s$ will be a part of $\oplus\Omega_0$

Based on Equation (5), the designed product will meet the descriptions of the design. Obviously, if $\oplus\Omega_s$ is a part of $\oplus\Omega_0$, then Eq. (4) is satisfied. At the beginning of the design process, $\oplus\Omega_s$ is an unknown and $\oplus\Omega_0$ is the only thing defined. The truth-value of P^d is undetermined, which means the request is yet to be met.

According to equation (2) and (3), we have

$$\oplus\Omega_0 = (\oplus E_0) \cup (\oplus S_0) \cup B_0, \qquad (6)$$
$$\oplus\Omega_s = (\oplus E_s) \cup (\oplus S_s) \cup B_s .$$

Finally, the following equation can be derived as follow:

$$P^d = \lambda(\oplus E_0, \oplus E_s) \wedge \lambda(\oplus S_0, \oplus S_s) \wedge \lambda(B_0^s, B_s^s) \wedge \lambda(B_0^a, B_s^a) \wedge \lambda(B_0^r, B_s^r), \qquad (7)$$

where the symbol $\wedge$ denotes logical "and", and both B_0^i and B_s^i are defined as follows:

$$B_0^i = (E_i \otimes S_0) \cup (S_0 \otimes E_i), \qquad (8)$$
$$B_s^i = (E_i \otimes S_s) \cup (S_s \otimes E_i).$$

Two theorems are derived from equation (7): structure of design problem and sources of product requirements.

Structure of requirements: A design problem is composed of three parts: the environment in which the designed product is expected to work, the requirements for product structure, and the requirements for performances of the designed product. This theorem is shown in Table 1.

Table 1 Elements of design problem (Zeng, 2004)

Design Problem P^d	
Product Environment	E_2
Performance Requirements	$\lambda(B_0^a, B_s^a) \wedge \lambda(B_0^r, B_s^r)$
Structural Requirements	$\lambda(\oplus S_0, \oplus S_s) \wedge \lambda(B_0^s, B_s^s)$

Source of product requirements: The product environment in which the product is expected to work imposes all the design requirements in a design problem.

In general, the product environment can be partitioned into a finite number of sub-environments:

$$E = \bigcup_{i=1}^{n} E_i, \exists E_1, E_2, \cdots, E_n, \forall i, j, i \neq j, E_i \cap E_j = \Phi, \tag{9}$$

where n is a finite positive number. Each E_i can be an individual environment. It can be observed that any product will work in three environments: natural, built, and human, which are denoted by E^n, E^b, E^h respectively. Thus we have:

$$E = E^n \cup E^b \cup E^h. \tag{10}$$

By the environment-based formulation of design problem, we can conclude as follows:

- The requirements of product in design process derive from the relationship between a product and environments in which the product will work.

- The structural and functional requirements come from the different relationship between the product and its environments.
- The environments in which the product works can be divided into three types: natural, built, and human environments.

According to the environment-based design theory, the sources of product requirements are the relations between the product and its environments. In order to obtain the satisfied requirements, identifying the environment components and their relations are two major issues. However, in this theory, Dr. Zeng did not discuss the detailed environment components involved in a product life cycle, and he did not present the relations classification. Therefore, there are two problems in the current environment-based design theory for gathering product requirements.

- *Problem 1: How to identify the environment components based on product life cycle*
- *Problem 2: How to identify the relations between the product and its environments*

In the following Chapter 3 and Chapter 4, the author develops two sets of ontology for solving the two problems.

2.4 Summary

In this chapter, the author reviews the design process, design strategies, and design theory that is used in developing design requirements. As the starting point of a design process, identifying the requirements and stating the design problem is of critical important once for a successful design. Although there are many tools and concepts that help the designers to do the job, the lack of a systematic approach, that can trace the source of requirements, classify the requirements, and manage the requirements, is a reality and challenge for the designers. In the rest of this present theory, the author aims to extend the environment-based design theory for gathering product requirements, by further classifying environments in which a problem is expected to work and the relations between them.

Chapter 3 **Environments in a Product Life Cycle**

In the last chapter, the author reviews the environment-based design theory (Zeng, 2004) and proposes to extend the environment-based design theory for gathering product requirement by addressing the following two problems:

- *Problem 1: How to identify the environment components based on product life cycle*
- *Problem 2: How to identify the relations between the product and its environments*

In this chapter, the author aims to identify environment components in which a product is expected to work throughout the product life cycle. Relations between the product and its environments are presented in Chapter 4.

3.1 Environment components for a product design

Based on the environment-based formulation of design problems (Zeng, 2004), a product environment contains three sub-environments: natural, built, and human, as is shown in Figure 8. This corresponds to Equation 10 in Chapter 2.

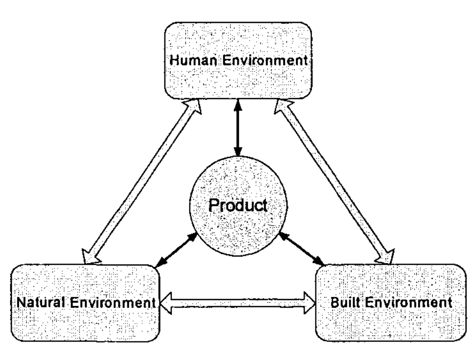


Figure 8: Environment components for a product design

Natural environment refers to all natural phenomena and natural laws. For example, the natural environment for a typical medical device contains such factors as temperature, humidity, and light. Built environment includes all artefacts created by human beings. These artifacts can be products or other instruments in the same room, the building in which the device is put. It is sometimes difficult to distinguish between natural and built environments. Designers must predict the influence of interactions among those environmental components. The more complex the interactions between the products are, the bigger the challenges are for product designers to face. Human environment includes diverse human users in the life cycle of a product. Users can be not only doctors and patients, but also salesmen or device maintainers of a product. As a matter of fact, each of the three environments does not exist by itself, they interact with one another.

In order to formulate product design problem based on its environment, the designer must identify the product and its environment as well as their relationships. The identified environment can be classified in terms of product life cycle or the three types of environments introduced above. There may be many relationships between a product and its environment. To analyze the requirements for a product design, we will first substitute equation (10) into equation (1) and reveal what elements we have to consider.

$$\Omega = E^n \cup E^b \cup E^h \cup S. \quad (11)$$

And then we have

$$\oplus\Omega = \oplus(E^n \cup E^b \cup E^h \cup S) \qquad (12)$$
$$= (\oplus E^n) \cup (\oplus E^b) \cup (\oplus E^h) \cup (\oplus S) \cup$$
$$(E^n \otimes E^b) \cup (E^n \otimes E^h) \cup (E^n \otimes S) \cup$$
$$(E^b \otimes E^n) \cup (E^b \otimes E^h) \cup (E^b \otimes S) \cup$$
$$(E^h \otimes E^n) \cup (E^h \otimes E^b) \cup (E^h \otimes S) \cup$$
$$(S \otimes E^n) \cup (S \otimes E^b) \cup (S \otimes E^h).$$

As it can be seen from equation 12, 12 relations are included in defining a product design requirements.

3.2 Life-cycle concept

The product life cycle has been represented in many ways. Research over the past decade has focused on reducing the impact of the product throughout this life-cycle and has also focused on attempting to ensure that the product life-cycle be re-iterated as many times as possible for one product.

LCA, known as "life-cycle assessment", is a technique used in the product life cycle consideration. The attempt to bring LCA closer to the design team by providing tools is to help designers to make decisions in the company's design process. However, it is limited to the environmental impact of a product.

Concurrent engineering (CE) is the other concept used in the process of the product development by life-cycle thinking. In concurrent engineering literature, Kannapan and Marshall (1992), and Cleetus alike (1992) have provided a definition of CE that extends the terms to the consideration of a product through its life cycle, from concept to end-of-life, and beyond:

"Concurrent Engineering, in the ideal case, brings to bear all concerns throughout the product life-cycle during product design. The strategy of concurrence provides an opportunity to address the source of conflicts between design agents representing the concerns of different engineering disciplines, functionality, marketability, manufacrurability, maintainability, etc. early in the engineering process." (Kannapan and Marshall, 1992)

Concurrent engineering is an effective and powerful methodological philosophy for obtaining the most satisfying product design possible from an integrated and global viewpoint. The products to be manufactured are related with the product life phases. In the product design stage, the ideal status is to consider the completely comprehended information obtained from each issue of the product life cycle. However, looking then at the design theories and the industrial practices, there are two typical status in design practices.

- Many design models go only as manufacturing and selling the product, after which time the company's responsibility ends. In this case, very few designers go beyond the selling of a product to its usage, service, and disposal phases, thereby reflecting industry's traditional relationship with the products that they manufacture.
- In the second status, a designer focuses more on the ender-user's requirements and functionality of the product, so the impact of manufacturing and transportation is ignored in design stage.

At the design stage, since few details are known about the product that is being designed, it is not easy to consider all aspects of its life-cycle. Moreover, because of the complexity of products, it is difficult to expect designers to have a life-cycle philosophy without first understanding what the life cycle of a product really entails. If design models were used in line with the two statements made by Kannapan and Marshall, and Cleetus above, designers would be able to develop more of an understanding about the whole life of their products. However, that would be ideal situation.

3.3 Environments in product life cycle

The idea of a product life cycle acknowledges the fact that every product goes through a series of steps between the time it is first conceived and the time the manufactured product is retired or discarded (Mahendra S. Hundal, 2002). Although a product is protean, basically, a mechanical product life cycle can be divided into design stage, manufacturing stage, distribution stage, usage stage, and retirement stage. Figure 9 shows one view of the various phases of a mechanical product lifecycle.

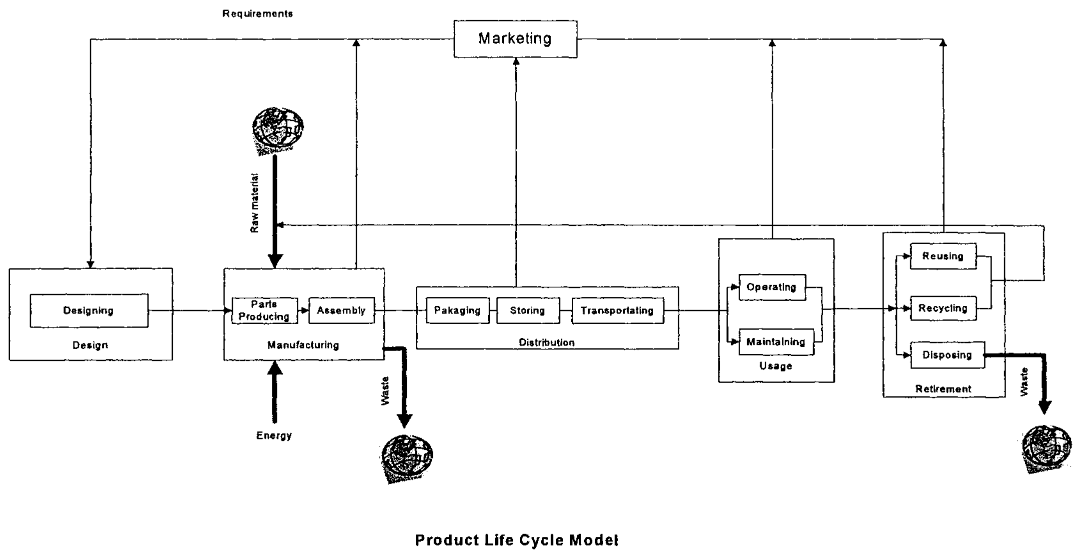


Figure 9: Product life cycle model

Based on the environment-based design theory (Zeng, 2004), any product will work in three environments: natural, built, and human. To work in natural environment, a product should obey all natural laws and rules. For example, a product exits on earth, it conform to Newton's laws. Otherwise, the product would not be able to survive and exist. The built environments include that all artificially built or created by human beings. For example, in engineering design, there are many standards and regulations set up by people to compel the product to follow up. If a product is not consistent to those laws, it will not be allowed to be used. Moreover, the requirements such as manufacturalibility and transportability come from the built environments' requirements too. As we know, a product is expected to be used by human being. The human environments include all human beings that a product is gotten involved in the life cycle, such as operators, sellers, maintenance technician, and so on. Human factors and ergonomic factors must be considered in design, especially in interface design.

The following subsections will discuss the environmental components at each stage of product life –cycle.

3.3.1 Design stage

The design activity is that designers create a product or a service to meet customer's requirements by using technology and knowledge under constrains of regulations and standards. A product design starts with a need or opportunity in the marketplace. The following figure describes the design process. The input of design process is the requirements, and the output of the process is the drawings and documents of the final design.

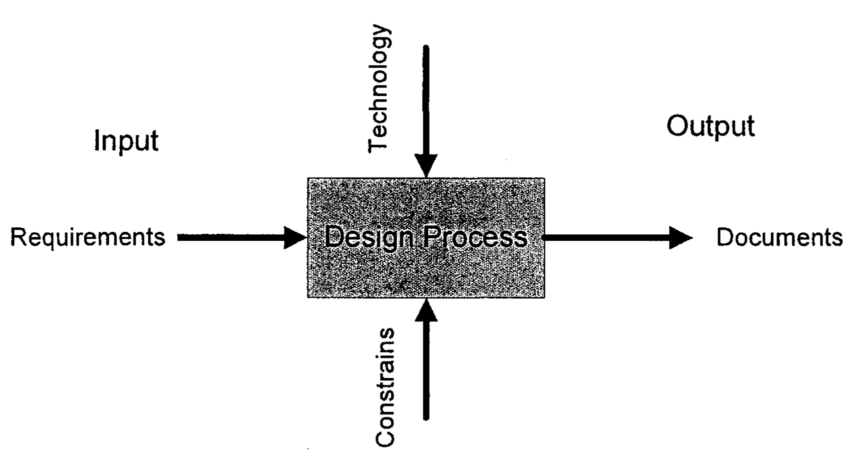


Figure 10: Input and output of design

The environment of the product in this stage is illustrated in Figure 11.

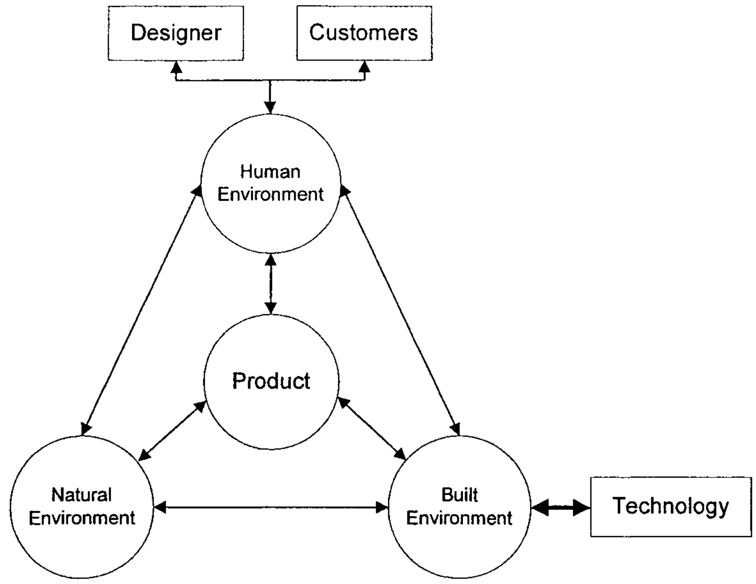


Figure 11: Environments in design stage

Human Environment: In the design stage, the human environment includes the designer and customers. A designer is a key person in the design process who analyzes the customer's needs and finds the solution to satisfy the customer's needs as much as possible. Usually, attributes of designer such as age, education, experience, and culture have influences on the product design. Customers are the other important human environment in the design stage. The input of the design process is the customer's requirements, which include external and internal customers. From the perspective of product life cycle, the external customers are the people who are outside of the organization, such as end-users, maintenance technician, etc. The internal customers are the people inside the organization, such as workers in manufacturing, seller, etc. The customer's requirements are not only from external customers but also internal customers. For example, functional requirements come from the usage stage, which present what the product is able to perform. The requirements from manufacturing stage consider that how the product can be produced correctly. If a designer collects all the requirements from the every stage of the product life cycle, the task of collecting requirements would be well done.

Built Environment: Built environments in design stage include the technologies that are used to solve the design problem and the standards and regulations, that are mandatory to the product. Due to various technical constrains in different contexts, technical limitations should be considered in the design stage. Some requirements may not be able to be realized with capacity of the available technologies. Therefore, technology determines the probability of the product development. Not only technology but also the standards and other mandatory criteria must be considered firstly. Otherwise, even though the product can be designed and produced, it cannot be approved into the market.

3.3.2 Manufacturing stage

Once the design is completed, the design drawings are passed to the manufacturing department for prototyping or producing the final product. Many manufacturers like to purchase the rough parts rather than to produce them. However, if we consider the process in a big global view, the manufacturing process is from the time raw materials enter the manufacturing plant to when a finished product leaves the shop floor, including material selection, parts producing, and assembly. The input of the manufacturing process is material, design documents, and energy used in process. The output of the manufacturing process is the product. Figure 12 presents the process.

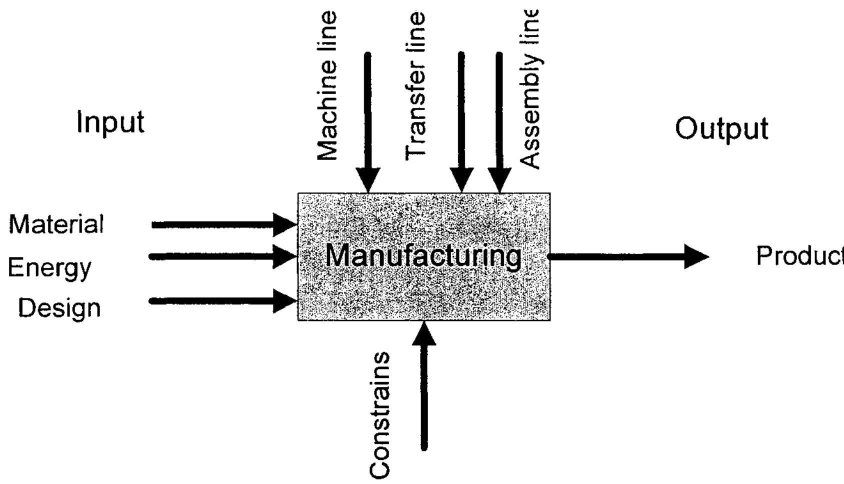


Figure 12: Input and output of manufacturing process

Traditionally, the attitude of designers has been "we design it, you built it". In this status, many manufacturing problems, such as setup costs, consistency with existing manufacturing methods, or excessive complexity, cause design to be modified. Hence, a good designer must consider the requirements of manufacturing process. The environments that a designer should consider in manufacturing stage are illustrated in Figure 13.

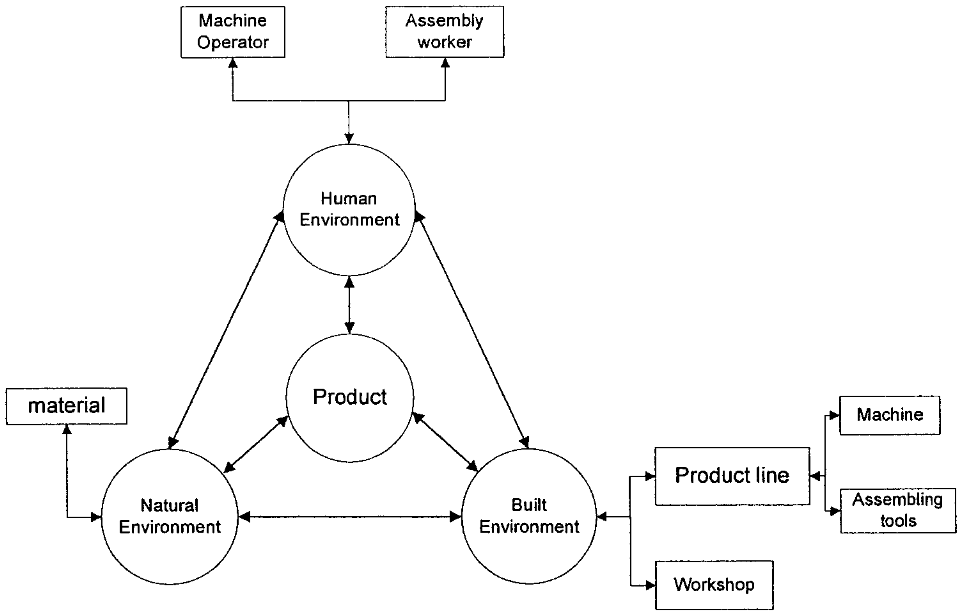


Figure 13: Environments in manufacturing stage

Human Environments: The human environment in manufacturing stage includes workers who participate in the product line, such as machining operator and assembly technician. In order to produce a good product, ergonomics of workers must be considered at the design stage to minimize ergonomics problems in performing jobs on the product line or in the workplace.

Built environments: The built environment we consider in manufacturing process includes the workshop, the product line, and the standards according to which the product should be completed. The workshop is a space in which the product is produced. The factors of workshop such as temperature and neatness have an influence on producing of the product. Since the product is different from the old products, the product line must be different so far as the modelling, machining, and assembling are concerned. In principle, the modelling process is identical to injection molding with a different class of materials. Many factors in modeling process, such as the machine used in the process and injection molds, influence the product attributes, geometry, tolerance, and surface condition. Similarly, in machining process, a designer should consider the ways in which the working material can be readily changed to the desired form by machining, and the ways in which the surfaces of the component are finished. Therefore, the factors in the machining process, including equipment, tools, and mediums, should be considered in the design process. In order to reduce the cost, decreasing machining and using existing machine is the major objectives of the designer. The designer should attempt to standardize the machined features to be incorporated in the design. It influences the parts design, especially in geometrical features of the product. By analyzing the environments in the assembly process, such as assembly tools and assembly line, designers is able to assure that considerations of product complexity and assembly take place at the earliest design stage. It helps designers to design features of parts, especially in joints and geometrics of parts.

Natural Environments: The consideration of natural environments in manufacturing stage is material selection and waste treatment. Since the selected material has direct influence on the product feature design, features of selected materials have been given considerable attention by designers. In the past, the requirements of material focus more on the material features and cost; however, along with more attention to HSE (health, safety, and environment) concerns, designers should consider more influence of materials on health and safety issue to human beings and on the environment issue during the process of mining, abstracting, and waste disposal.

3.3.3 Distribution stage

Distribution allows a company to get the product to customers. Generally speaking, it involves warehouse management and outbound transportation, including packaging, storage, and transportation. In terms of packaging, it should be ensured that the products are presented attractively and that packaging meets the regulatory requirements. The basic warehouse operation involves the movement and storage of goods, including receiving goods into the warehouse, transferring goods to a location in warehouse, and loading goods for shipment to the customers. Transportation involves the selection of carriers and moving product to consumers. Systematically, the environments in distribution stage are illustrated in Figure 14.

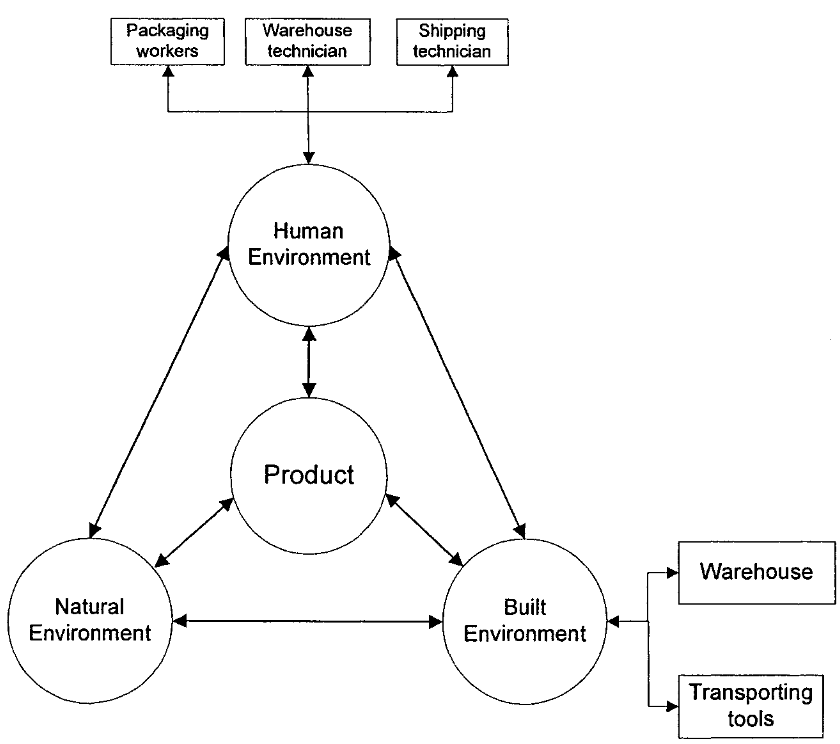


Figure 14: Environments in distribution stage

Human Environments: The human environments in distribution stage include workers who participate in the distribution management, such as packaging workers, warehouse technician, and shipping technician. Human factors must be considered. For example, ergonomic factors must be considered since it relates to product movement. Moreover, the interface such as labelling on the product and package should be paid more attention to since there are many errors because of incorrect labelling.

Built Environments: In the usage stage, major built environments include warehouse, transporting tools, standards, and regulation. By analyzing the effect of warehouse, designers can assure that the product can be stored properly. In thinking at the transportation tools limitation, designers can consider which kind of handle should be designed. Standards and regulation are very important in distribution stage. Packaging regulation requires the labelling requirements in language, colour, and introduction. Safety regulations ensure the product does not harm consumers, property or the environment. All the aspects should be considered in design process.

3.3.4 Usage stage

After the product is delivered to customers, it must be set up to operate to perform its functionality. The purpose of the product development is to develop a product to meet customer's use requirements. The key activity in usage stage is to operate the product by users. Major function requirements come from the usage stage. Moreover, during the operation, in order to perform the functionality, the product must be supported and maintained. The maintenance is the other important part in usage stage. The input of usage stage is the product, material, and energy. The output is the product functionalities.

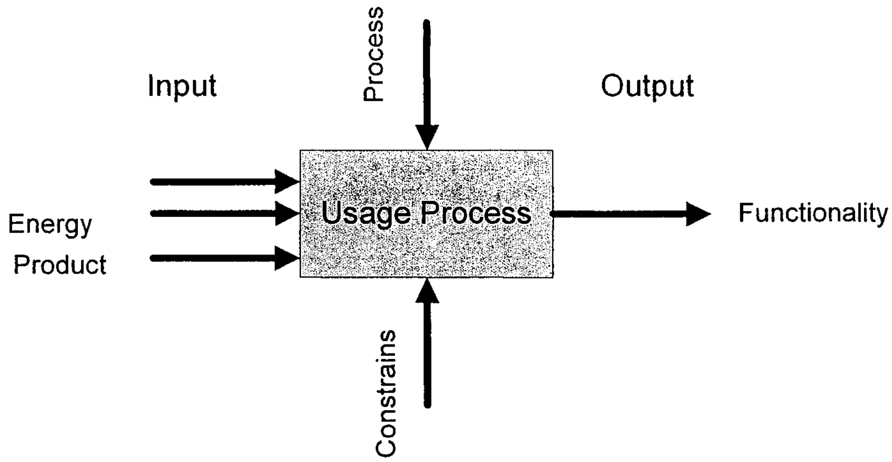


Figure 15: Input and output of usage stage

The environments should be considered in usage stage are illustrated in Figure 16.

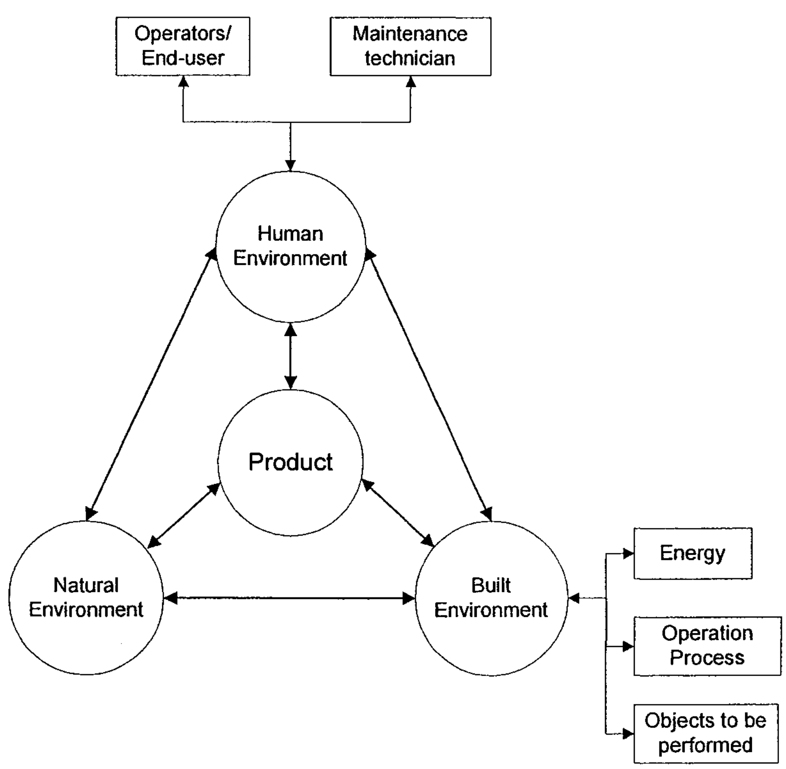


Figure 16: Environments in usage stage

Human Environments: The product performs its functionality by user operation. From an ergonomic perspective, one needs to address the question of what design elements are best suited to encourage friendly user behaviours. For a designer, analyzing the behaviours of users is useful to design a user-friendly product, including the control patterns, geometric product properties (shape, size), labelling, transparency, and feedback. Similarly, considering the maintenance technician factors, designers can optimize the structure of product in easy maintenance solution.

Built Environments: One way to better understand the product functionalities and deduce requirements is to analyze the objects that the product is expected to perform in their surroundings. Most of functional requirements come from the requirements how the product performs its job. Let's take a vacuum cleaner as an example, according to customers, the target that the vacuum cleaner cleans maybe is a carpet, wood floor, furniture, or others. Depending on the types of the targets and removed particles, the brush head, transporting system, and dust filter system will be designed in different ways.

3.3.5 Recycle stage

The end of life phase of a product begins at the moment a product loses its function or users no longer wish to use it. Recycling requirements has become an increasingly important dimension of environmental management for manufacturers in recent years in terms of the limited material on the earth and environmental awareness. Instead of throwing out the dead product, more and more designers must consider how to deal with the end life of the product because there is an increase in both magnitude and diversity of waste problems in affluent societies. Basically, there are three kinds of statues of materials after disassembling the product: reused parts, recycling material, and disposal waste that cannot be used again. Therefore, the input of the recycle stage is the product that loses its functions. The output is the disassembled material that can be recycled or disposed.

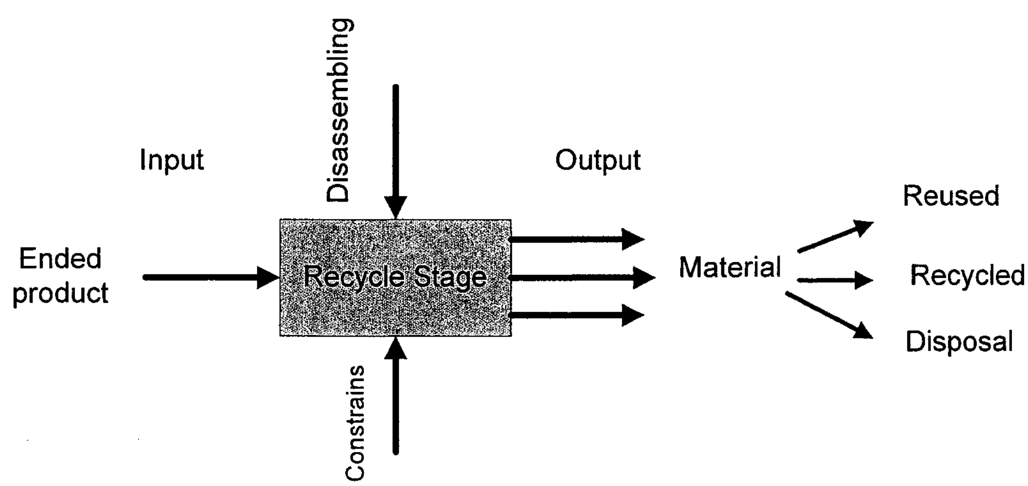


Figure 17: Input and output of recycling process

When a designer is designing a product, he or she must ask questions for concerning the end of life of product are as follows:

- Is the product taken back and reused?
- Are useful components or parts removed from the product for reuse or only the materials reused?
- How to treat the materials that cannot be recycled?
- Who is responsible to disassemble and recycle the product?
- Is there any legislation that must be followed?

In order to answer all the questions, the environments of recycle stage in product life cycle must be analyzed. Figure 18 presents the idea.

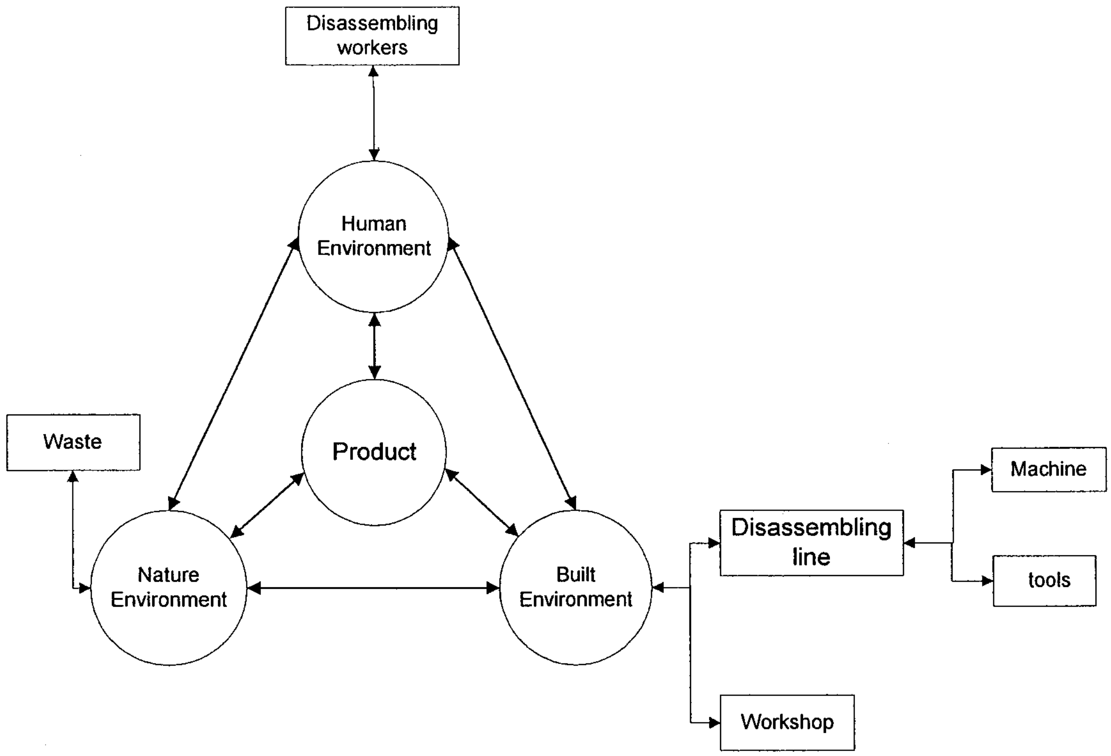


Figure 18: Environments in recycling stage

Human Environments: Considering the human environments in recycling stage, they include workers who participate in disassembling process, such as disassembling machining operator and technicians. Ergonomics of workers, health and safety issues must be considered to minimize problems in performing jobs.

Built Environments: The built environments in recycling stage include the workshop, the disassembling process, and the legislations. The workshop is a space in which the product is disassembled. The factors of workshop such as temperature and neatness have influence on the process. First step of recycling stage is disassembly. The disassembly billability relies on a good structure, which can only be obtained if taken into account during the early design phases. Therefore, first, a homogenous piece of material, a useful subassembly, and parts for reconditioning must be considered. Second, the surface of objects, called "separating surfaces", must be designed suitably. Separating surfaces can arise at several different joints such as screw joints, snap fits, and glue joints but also through a drop in strength somewhere inside the part. Throughout the analysis of disassembly machines and tools, we can get more requirements of structure.

Natural Environments: Most of the natural environmental effects related to a design will arise from material choice, processing, usage, and final disposal. In the recycling stage, environmental concerns focus on the disposing material that cannot be reused and sent to landfill. Considering the materials selection and waste bring out during disassembling process is essential. Requirements of recycling can be derived from by analyzing the natural environment and understanding their relationship.

3.4 Summary

One way to better understand the product system and to deduce requirements are to analyze the product's surrounding, the interaction with its neighboring systems, such as other technical product, other people and their surroundings. By using environment-based design theory (Zeng, 2004), the product's surrounding can be divided into natural environment, built environment, and human environment. At the same time, a product works through its life cycle, including design, manufacturing, distribution, usage, and recycling. If we want to get better analysis of environments that the product is expected to work, we should put the product into every stage of the product life cycle. In this chapter, the author identifies the environment components at each stage of a product life cycle, which are summarized in Table 2.

Table 2: Environment components in a product life cycle

Stage	Environment		
	Human Environment	**Built Environment**	**Natural environment**
Design stage	Designer	Technology	
	Customer	Regulation	
Manufacturing stage	Machine operator	machine line	Material
	Assembly worker	Transfer line	
		Assembly line	
		Workshop	
Distribution stage	Package worker	Warehouse	
	Warehouse technician	Transporting tools	
	Shipping technician	Packaging case	
Usage stage	End-user	Energy	Pollution
	Maintenance technician	Operation process	
		Objects to be performed	
Recycle stage	Disassembly worker	Disassembling line	waste
		workshop	

Chapter 4 **Relations**

In the previous chapter, the author develops an ontology to present the environment components that a product is expected to work in a product life cycle. This ontology is used to solve the problem 1. In this part, the author is going to classify and further define the relationships between a product and its environments by using an ontology of relations, which is used to solve the problem 2. Ontology is the branch of philosophy concerned with the meaning of existence in the broadest sense (Zeman 1984) by articulating the nature and structure of the world (Wand and Weber 1993). The subject of ontology is the study of the categories of things that exist or may exist in some domain (Sowa 2000). In the first part of this chapter, the author classifies the relations of objects in universe defined in the axiomatic theory of design modelling (Zeng, 2002). Understanding the natural relations of two objects in universe is fundamental to analyze the relationships between a product and its environments. The ontology of relations between a product and its environments is discussed in the second part of this chapter.

4.1 Relations of natural objects in universe

The axiomatic theory of design modeling is a logical tool for representing and reasoning about object structures (Zeng, 2002). The key concept in this theory is the relation between two objects. Zeng defines two categories of relations in two corollaries based on one of the five axioms he has proposed:

[Corollary 1] Every object in the universe includes other objects. Symbolically, it is denoted by:

$$A \supseteq B, \forall A, \exists B. \tag{13}$$

B is called a sub object of A. The symbol $\supseteq$ is inclusion relation. The inclusion relation is transitive and idempotent but not commutative. The components of a product are treated as sub-objects of the product.

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

$$C = A \otimes B, \forall A, B \exists C. \tag{14}$$

Where C is called the interaction object of A on B. The symbol $\otimes$ represents interaction relation. Interaction relation is idempotent but not transitive or associative.

Naturally, for the relations of two objects (O_1 and O_2), there are four relations, a relation of O_1 to O_2, a relation of O_2 to O_1, a relation of O_1 to itself, and a relation of O_2 to itself. They are illustrated in following Figure 19.

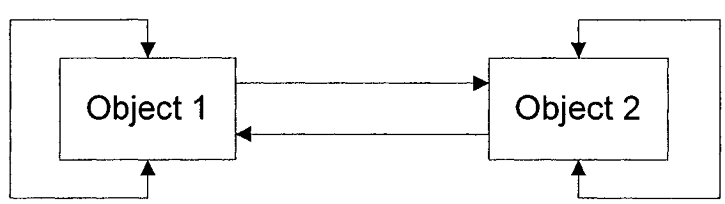


Figure 19: Relations between two objects

Definitely, relation is an aspect or quality that connects two or more objects as being, or belonging, or working together, or as being of the same kind. Relation can also be a property that holds between an ordered pair of objects. Therefore, different types of relations will lead to different concrete axiomatic system.

4.1.1 Types of relations

Relations are classified by many ways: degree, connectivity, cardinality, direction, type, and existence. Not all modeling methodologies use all these classifications. The degree of a relationship is the number of entities associated with the relationship. Binary relation, the association between two entities, is the most fundamental type in the real world. Multiple-relations can be regarded as combination of binary relations. In the present thesis, the author aims to analyze the binary relations between objects.

In the axiomatic theory of design modelling, two objects are considered, which are nature (N) and human (H) in terms of Figure 19. Their relations can be illustrated in Figure 20.

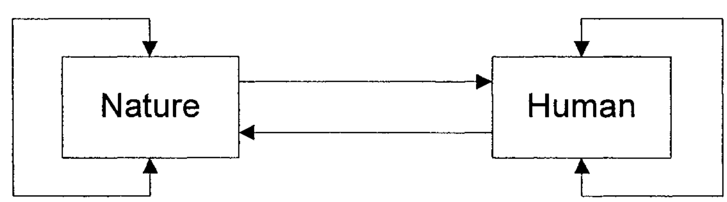


Figure 20: Relations between nature and human

There exist three binary relations in Figure 20: the relations between the objects in the nature (N ⊗ N), the relations between the nature and human ((N ⊗ H) and (H ⊗ N)), and the relations between the humans (H ⊗ H).

4.1.1.1 Relations between nature and nature (N ⊗ N)

All things are related in the world, directly or indirectly. Direct relations present the objects that are related to each other through a relationship that may be observed or act directly on each other, like the collision and the friction. Indirect relations present the relationships that are not observed or the objects act on each other by mediums, such as wave and field.

Typically, direct relations can be divided into two categories: static and dynamic. There are two typical presentations in static relationships: intersection and containment.

- *Intersection relationship* presents the two objects (A and B) conjunct with each other, written by $A \cap B$. In this case, the connection types, relative joints, and surface condition should be designed to solve the design problems. Deriving from this relationship, we can get the requirements on geometry, interface, tolerance, and so on.
- *Containment* presents relationship that all parts of the object B are contained in the object A. We say that A contains B, which is written by $A \supset B$. For example, in injection molding process, the relationship between mold and the part that will be produced is typical containment relation. The factors of geometry and tolerance should be considered in design.

In the universe, dynamic model of direct relations presents the situation of two objects changes at runtime, such as distance, structure, energy, etc. Basically, dynamic relations between the objects are mechanical and chemical.

- The mechanical interactions between two objects change the motion or the shape of the objects by force. For example, machining process is a typical mechanical relationship between a machine and a product. After machining, the product may be changed in its shape and structure in order to meet the requirements. When we look into the product life cycle, machining, mining, and casting are typically mechanical relationships between two objects. In a mechanical relationship between objects, designers should take into account force, tolerance, shape, and so on.

- Chemical interaction between objects is another dynamic relationship. Different with mechanical relations, Chemical interactive relations between objects mainly produce the change and the influence on characteristics, attributes, and features of the objects. In a product life cycle, refining material, additive moulding, and waste treatment are the classically chemical interactions in the mechanical design.

Besides direct relations, indirect relations are other representation of relations. Relations that do require a medium in order for the relation to function are called indirect relations. Field relation is one of the major types of indirect relations. In the nature, there exist many fields, such as magnetic field, temperature field, gravitational field, sound field, radiant field, and electrical field. Although there is no direct contact between objects, the fields between objects influence on the objects' performances and attributes. As we know, the same product may perform really differently when it works in a lower temperature environment or a high temperature environment. Moreover, the field influence induces a product failure in many cases, especially in electronic products. For example, according to a report from Medical Device Safety Reports (1987), one brand of pulse oximeters used with a disposable infant flex probe started displaying "Probe off Patient" when under a hospital-constructed radiant warming unit. Covering the probes with a towel or blanket did not prevent the problem. As soon as the warmer was turned off, the oximeters returned to normal operation. The radiant warming unit included two 250 W infrared (IR) heat lamps and a household dimmer switch, which was used to control the power to the lamps and, thus the radiated heat. It was determined that high frequency electrical interference from the dimmer switch was the source of the problem. It is typical field relationship between the oximeter and the environment.

Technology, standards, regulation, and laws are the knowledge invented or built by human beings. In the axiomatic theory of design modelling, they are also regarded as objects. The relationship between them and the product is indirect relationship because they cannot act on the product directly. They must act or constrain the product through human's response. The relations between two natural objects are summarized in Table 3.

Table 3: Relations between non-human objects

Event	Type		Form	Example	Factor
Object-object $N \otimes N$	Direct relation R_D^n	Static relation R_{DS}^n	Intersection	Connection	Relative Joint
				Contact	Surface condition, interface, geometry
			Containment	Contain	Geometry
		Dynamic relation R_{DD}^n	Mechanical	Machining	Structure, form, interface, tolerance
				Performing	Force, energy
				Coating	Surface condition, tolerance
			Chemical	Injecting	Pollution, feature
				Refining	Feature
	Indirect relation R_I^n	Field relation R_{IF}^n	Physical	Magnetic, gravitational, electrical	Force, energy
			Physical	Temperature, sound, Humidity	Energy
		Constrain relation R_{IC}^n	×	Knowledge, technology	×
			×	Standards, regulation, law	×

("×": Not applicable)

4.1.1.2 Relations between nature and human ((H ⊗ N) and (N ⊗ H))

Natural objects and human beings together constitute the world. The correlation of objects and human are two ways. First, human beings can move transforms the object, influence the objects, causes the objects to satisfy human's goals and requests. This is the relation from human to objects. Second, the object influences human's cognition and understanding. This relation is the influence of objects to human beings. Basically, the correlation of humans and objects can be divided into two types: physical relations and mental relations.

The main functions of humans to objects are to create a product and use it to meet human's requirements. Creation process is a process that human beings invent something by using their knowledge. It is an intellective activity. The culture, emotion, and knowledge of humans are the major factors that should be considered in a design process. The second function of human to objects is to use an object to satisfy human goals and requirements. These are physical relations between humans and objects. User experience and interface design in the context of creating products represents an approach that puts the user, rather than the system, at the center of the process. This philosophy, called user-centered design, incorporates user concerns and advocacy from the beginning of the design process and dictates that the user's needs should be foremost in any design decisions. Today, Ergonomics commonly refers to designing work environments for maximizing safety and efficiency. When we refer to a product life cycle, the physical relationships of humans to a product include transforming, operating, maintaining, etc. In order to improve working effectiveness and efficiency, the interface including structure and geometry of the product should accord with ergonomics.

The influence of objects on humans is also physical and mental. From the point of view of the physical influence, an object has the constraint of usage to predict the physical injure on human bodies. The weight, size, structure, and interface constrain the product's usability. In the other word, physical relation of objects to people is safety and efficiency issue. Mental influence to humans includes two manifestations, concentration and response. Mental Concentration, in practice, consists of focusing the mind upon a given subject, or object, firmly and fixedly, and then holding it there for a certain time, fully intent upon its object, and not allowing itself to be diverted or attracted from its object. It likewise consists in the correlative power of then detaching the mind from that subject, or object, and either allowing it to rest, or else focusing it upon another object. In other words, concentration either gives undivided attention to an object or else inhibits attention towards the given subject or object. Hence, the quality of a product design directly affects user's attention and recognition. Secondly, mental response for objects includes imaging and reflecting. Imaging process is to describe to others scenes that one has witnessed, occurrences, details of appearances, etc., until one is able to reproduce mentally the aspects and appearances of the things. Then one may begin to draw mental pictures of things desired as if they were being drawn on the screen of one's mind. Reflection is thinking for an extended period to promote a more complex and interrelated mental schema after you image the screen. The thinking involves looking for differences and interrelations beyond their superficial elements, and then one can carry out the activity to perform the task. Ergonomics ("fitting the job to the worker") is a multidisciplinary activity having to do with the work situation. Its objective is to achieve an optimum man/task system in which a proper balance can be maintained between the worker and the working conditions. Thus it is suited to evaluating more complex work situation that result from rapidly changing technology. From physical angle, ergonomic consideration includes light, sound, vibration, etc, which influence the human's performance to do a job. From the mental angle, those factors also influence the mental loading to humans. Kong (2005) addressed this issue in details in his Master's thesis. The relations between nature and humans are summarized in Table 4.

Table 4: Relations between human and non-human objects

Event	Type	Form	Factor
Human-object $H \otimes N$	Physical relation R_P^{hn}	Movement	Handle, weight, size
		Operation (using)	Interface, operation ability, ergonomics, human factors
		Maintenance	Assembly ability
	Mental relation R_M^{hn}	Creation	Knowledge, culture, emotion, skills
		Cognition	Interface
Object - human $N \otimes H$	Physical relation R_P^{nh}	Field influence	Noise, vibration, radial
		Physical loading	Weight Size, Interface
	Mental relation R_M^{nh}	Cognition	Color, appearance, figure
		Mental loading	Complexity

4.1.1.3 Relations between humans and humans (H ⊗ H)

The relation between human and human is another very important relationship in the universe. However, it is irrelevant for a product design. It constitutes the foundation for social science.

4.2 Relations between a product and its environments in the product life cycle

In the past section, the author has discussed the relations between objects and their environments in the product life cycle. In this section, the author refines the relations between a product and its environments based on the types of environments identified in Chapter 3. Basically, the relations between a product (S) and its environments (E) include the relation of the product itself (S ⊗ S), the relation of the product to the environments (S ⊗ E), the relation of the environments to the product (E ⊗ S), and the relation of the environments to the environments (E ⊗ E), which is illustrated by the following Figure 21.

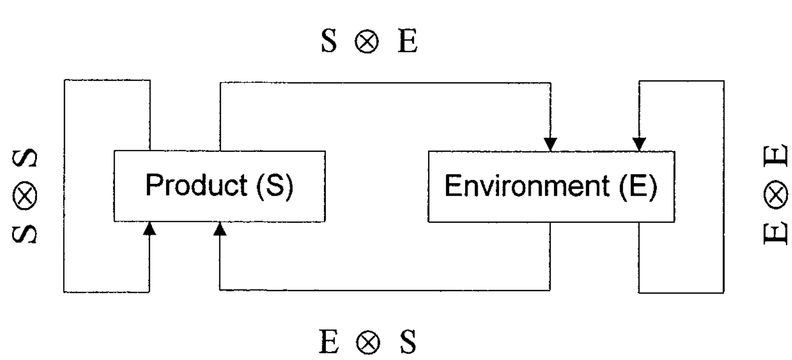


Figure 21: Relations in a product system

A template of table 5 will be used to classify the relations.

Table 5: Template for the representation of relations

<table>
<tr><td colspan="2" rowspan="2">Stage</td><td rowspan="2">Product (S)</td><td colspan="5">Environments (E)</td></tr>
<tr><td>E1</td><td>E2</td><td>E3</td><td>E4</td><td>E5</td></tr>
<tr><td colspan="2">Product (S)</td><td>$S \otimes S$</td><td colspan="5">$S \otimes E$</td></tr>
<tr><td rowspan="5">Environments (E)</td><td>E1</td><td rowspan="5">$E \otimes S$</td><td colspan="5" rowspan="5">$E \otimes E$</td></tr>
<tr><td>E2</td></tr>
<tr><td>E3</td></tr>
<tr><td>E4</td></tr>
<tr><td>E5</td></tr>
</table>

Tables 6 to Table 10 are the relations between a product and its environments at each stage of the product lifecycle according to ontology of relations presented in Table 3 and Table 4. The meanings of the symbols are as follows:

R_{DD}^{n}	Nature to nature	Directly dynamic relation
R_{DS}^{n}	Nature to nature	Directly static relation
R_{IF}^{n}	Nature to nature	Indirectly field relation
R_{IC}^{n}	Nature to nature	Indirectly constrain relation
R_{P}^{hn}	Human to nature	Physical relation
R_{M}^{hn}	Human to nature	Mental relation
R_{P}^{nh}	Nature to human	Physical relation
R_{M}^{nh}	Nature to human	Mental relation
×		Weak relation or irrespective

Table 6: Relations between a product and its environments in the design stage

Design Stage		Product	Environments			
			Designer	Customers	Technology	Natural environment
Product		×	×	$R_P^{nh} + R_M^{nh}$	×	R_{IF}^{n}
Environments	Designer	R_M^{hn}	×	×	×	×
	Customers	R_P^{hn}	×	×	×	×
	Technology	R_{IC}^{n}	R_M^{nh}	×	×	×
	Natural Environment	R_{IF}^{n}	×	×	×	×

In design stage, designers create the product draft by using technology. The relation of designers to product is mental relation of human to nature (R_M^{hn}), and the relation of technology to product is indirectly constrain relation (R_{IC}^{n}). Customers use and maintain the product, so the relation of customers to product is physical relation of human to nature (R_P^{hn}). At the same time, technology influence designers' creation. The relation of technology to designers is mental relation of nature to human (R_M^{nh}). The structure and functions of product affect customer's physical and mental loading, so the relations of product to customers are physical and mental relations of nature to human ($R_P^{nh} + R_M^{nh}$). The relations between product and nature environment are indirect field relation of nature to nature (R_{IF}^{n}).

Table 7: Relations between a product and its environments in the manufacturing stage

Manufacturing Stage		Product	Environments						
			Machine Operators	Assembly workers	Material	Machine	Assembly tools	Workshop	Natural Environ.
Product		×	$R_P^{nh}+R_M^{nh}$	$R_P^{nh}+R_M^{nh}$	×	×	×	×	R_{IF}^{n}
Environments	Machine Operators	R_P^{hn}	×	×	R_P^{hn}	R_P^{hn}	×	×	×
	Assembly workers	R_P^{hn}	×	×	×	×	R_P^{hn}	×	×
	Material	R_{DD}^{n}	$R_P^{nh}+R_M^{nh}$	×	×	R_{DD}^{n}	×	×	R_{DD}^{n}
	Machine	$R_{DS}^{n}+R_{DD}^{n}$	$R_P^{nh}+R_M^{nh}$	×	R_{DD}^{n}	×	×	×	×
	Assembly tools	R_{DS}^{n}	×	×	×	×	×	×	×
	workshop	R_{IF}^{n}	R_{IF}^{n}	R_{IF}^{n}	R_{IF}^{n}	R_{IF}^{n}	R_{IF}^{n}	×	×
	Natural Environ.	R_{IF}^{n}	×	×	×	×	×	×	×

In manufacturing stage, machine operators use machine to produce the product or parts, and assembly workers assemble parts by using assembly tools. The relations of machine operator and assembly worker to product are physical relation of human to nature (R_P^{hn}). On the other hand, the complexity of product influence the physical and mental loading of machine operator and assembly worker, so the relations of product to machine operator and assembly worker are the physical and mental relations of nature to human

($R_P^{nh} + R_M^{nh}$). The relations of machine operator to machine and assembly worker to assembly tools are physical relation of human to nature (R_P^{hn}). In contrast, the relations of machine to machine operator and assembly tools to assembly worker are physical and mental relations of nature to human ($R_P^{nh} + R_M^{nh}$).

Material is an important environment component in manufacturing stage. First, raw material is refined from nature, so the relation of material to nature is directly dynamic relation of nature to nature (R_{DD}^{n}). Second, the features of material influence structure and functionality of product. The relations of material to product are directly static and dynamic relations of nature to nature ($R_{DS}^{n} + R_{DD}^{n}$). Third, during the manufacturing process, the features of material influence the machine's manufacturability and operator's physical and mental health. The correlated relations of material and machine are directly dynamic relations of nature to nature (R_{DD}^{n}). The relations of material to operator are physical and mental relations of nature to human ($R_P^{nh} + R_M^{nh}$). In contrast, the relation of operator to material is physical relation of human to nature (R_P^{hn}).

Natural environment and workshop also influence the other components, and their relations are indirect field relation between nature and nature (R_{IF}^{n}).

Table 8: Relations between a product and its environments in the distribution stage

Distribution Stage		Product	Environments				
			Package workers	Warehouse technician	Transportation tools	Workshop	Natural Environments.
Product		×	$R_P^{nh}+R_M^{nh}$	$R_P^{nh}+R_M^{nh}$	×	×	×
Environments	Package workers	$R_P^{hn}+R_M^{hn}$	×	×	R_P^{hn}	×	×
	Warehouse technician	$R_P^{hn}+R_M^{hn}$	×	×	R_P^{hn}	×	×
	Transportation tools	$R_{DS}^{n}+R_{DD}^{n}$	$R_P^{nh}+R_M^{nh}$	$R_P^{nh}+R_M^{nh}$	×	×	×
	workshop	R_{IF}^{n}	R_{IF}^{n}	R_{IF}^{n}	R_{IF}^{n}	×	×
	Natural Environments	R_{IF}^{n}	×	×	×	×	×

In distribution stage, the major activities are packaging and transportation. The product has influence on human physical and mental loading, so the relations of product to package work and warehouse technician are physical relations of nature to human ($R_P^{nh}+R_M^{nh}$). In contrast, the relations of human environment to product are physical and mental relations of human to nature ($R_P^{hn}+R_M^{hn}$). Transportation tools such as crane and truck are very important environment components. The relations of transportation tools to product are directly static and dynamic relation of nature to nature ($R_{DS}^{n}+R_{DD}^{n}$). The complexity of transportation tools has influence on worker's physical and mental loading, so the relations of transportation tools to workers are physical and mental relations of nature to human ($R_P^{nh}+R_M^{nh}$), and the relation of workers to transportation tools is physical relation of human to nature (R_P^{hn}). Of course, natural environment and warehouse has influence in distribution stage, and their relations are indirect field relation (R_{IF}^n).

Table 9: Relations between a product and its environments in the usage stage

Usage Stage		Product	Environments					
			Operators /end users	Maintenance technician	Power	Objects to be performed	Workshop	Natural Environments
Product		×	$R_P^{nh}+R_M^{nh}$	$R_P^{nh}+R_M^{nh}$	×	$R_{DS}^n+R_{DD}^n$	×	×
Environments	Operators /End -users	R_P^{hn}	×	×	×	×	×	×
	Maintenance technician	R_P^{hn}	×	×	×	×	×	×
	Power	R_{DD}^n	×	×	×	R_{DD}^n	×	R_{DD}^n
	Objects to be performed	$R_{DS}^n+R_{DD}^n$	×	×	R_{DD}^n	×	×	×
	workshop	R_{IF}^n	R_{IF}^n	R_{IF}^n	R_{IF}^n	×	×	×
	Natural Environments	R_{IF}^n	×	×	R_{DD}^n	×	×	×

In the usage stage, end-user uses and maintains the product for performing the job. The relation of users or maintenance technician to product is physical relation of human to nature (R_P^{hn}). The relation of product to user or maintenance worker is physical and mental relation of nature to human. The correlated relations between product and performed objects are directly static and dynamic relations of nature to nature ($R_{DS}^n+R_{DD}^n$). Power system provides energy to product for performing the job. It has relationships with product, objected to be performed, and natural environment, and correlated relations are directly dynamic relations of nature to nature (R_{DD}^{n}).

Table 10: Relations between a product and its environments in the recycle stage

Recycle Stage		Product	Environments			
			Disassembly workers	Machine/tools	Workshop	Natural Environments
Product		×	$R_P^{nh} + R_M^{nh}$	×	×	R_{DD}^{n}
Environments	Disassembly workers	R_P^{hn}	×	R_P^{hn}	×	×
	Machine/tools	$R_{DS}^{n} + R_{DD}^{n}$	$R_P^{nh} + R_M^{nh}$	×	×	×
	workshop	R_{IF}^{n}	R_{IF}^{n}	R_{IF}^{n}	×	×
	Natural Environments	R_{IF}^{n}	×	×	×	×

In the recycle stage, the product is disassembled and treated for recycling, disposing, and reusing. The relations of product to disassembly worker are physical and mental relation of nature to human ($R_P^{nh} + R_M^{nh}$); in contrast, the relation of workers to product is physical relation of human to nature (R_P^{hn}). The relations of machine (or tools) to product are directly static and dynamic relations of nature to nature ($R_{DS}^{n} + R_{DD}^{n}$). Those are not recycled is disposed to natural environment, so the relation with natural environment is directly dynamic relation (R_{DD}^{n}).

4.3 Summary

By using the axiomatic theory of design modelling, the author divides the binary relations between the objects in nature into three kinds of binary relations: relations between nature and nature, relations between nature and human, and relations between human and human. Based on this, the author develops an ontology for relations. Finally, the author refines the relations between a product and its environments based on the environment components of product life cycle identified in Chapter 3. This ontology solves the problem 2 that is introduced at the end of Chapter 2.

Chapter 5 **Taxonomy for Product Requirements**

According to the environment-based design theory, requirements are derived from the relations between a product and its environments in which the product is expected to work. In the last two chapters, the author has discussed the environment components in the product life cycle and classified the relations between them. The goal of this chapter is to develop a taxonomy for classifying the product requirements in the product life cycle.

Taxonomy is a good method to organize a lot of information. It is common to many fields of science. The rules for creating taxonomy classifications have two common threads. Derr (1973) states that classed must be mutually exclusive and exhaustive. Dunn and Everett (1982) state that, "a taxon is a taxonomic of any rank that is sufficiently distinct to be worthy of being assigned to a definite category". In 1995, Gershenson and Stauffer proposed a taxonomy for customer requirements in four types requirements: end-user, corporate, technical, and regulatory requirements. In this present thesis, the author develops a taxonomy for product requirements to classify and manage the requirements.

5.1 Requirements on requirements

A requirement is a necessary attribute in a system, a statement that identifies a capability, characteristic, or quality factor of a system in order for it to have value and utility to a user (Rahph, 2001). Each good requirement should be complete, consistent, and traceable.

Complete: Good requirements include all the information because they are complete. Complete requirements specification must precisely define all the real world situations that are encountered in the product lifecycle. No requirements should be missing. For the requirements of a product design, many designers or customers focus more on functional requirements; however, some important requirements such as requirements caused by human factors are ignored. This is the reason why many products have problems when customers use them. For example, Between 1994 and 1996, the U.S. Food and Drug Administration (FDA) has received more than 400 medical device reports on blood glucose monitors (BGMs), and ECRI continues to receive reports of errors involving the use of these units in hospitals. Although hospitals have guidelines and policies in place for using BGMs, errors can increase when many different people use the units and when many different BGM brands are used. The major reason was that the devices were used, calibrated, and maintained improperly by different users. Therefore, for medical devices design, user characteristics must be considered in the process, such as their age, profession, educational background, technical expertise, as well as physical and mental conditions.

Consistent: Good requirements should be consistent. A consistent specification is one where there is no conflict between, on the one hand, individual requirement statements that define the behaviour of essential capabilities and, on the other hand, specified behavioural properties and constraints do not have an adverse impact on that behaviour. Stated in another way, capability functions and performance level must be compatible, and therefore the required quality features (reliability, safety, security, etc.) must not negate the capability's utility. For example, for a vacuum cleaner design, heavy-duty power is necessary for the performance of deep cleaning. However, this heavy-duty power causes other problems, such as noise and cost. In a good design, the consistency between requirements must be well considered.

Traceable: Each requirement achieves traceability by being uniquely identified. Each requirement should be able to be linked to its source, such as a higher-level system, a use case, or a voice-of-the-customer statement. An interface requirement usually comes from the ergonomic consideration of users. Material selection requirements usually vary according to the environmental factors. The traceability of requirements helps designers identify the root cause of a problem. Moreover, traceability aims at linking each requirement to the design element. A designer should know which requirement the element is designed to meet. This characteristic helps designers to modify the solution if a requirement changes.

In order to obtain a well-defined requirements structure, a good reliability management system should be developed to help designers gather and manage all the requirements from multi-sources, such as user, business, environment, and regulation. The basic process of requirements management can be divided into gathering or capturing stage, analysing stage, and storing stage, which is illustrated in Figured 22:

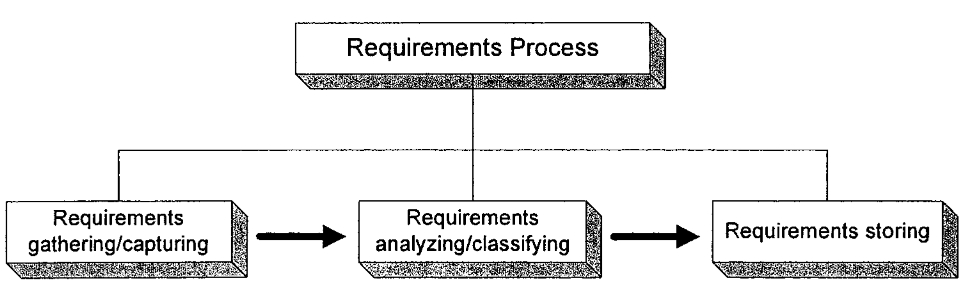


Figure 22: Requirements management components

Therefore, a requirements management system should be comprehensive in order to achieve the objectives. Since requirements are complex, it requires that the requirements management system is able to gather all the requirements from multi-sources. In the past, the development at design requirements focused on end-users and product functions. However, in the present, requirements from customers are not only from end-users but also from internal customers, such as manufacturer and salesperson. Moreover, the considered requirements for a product are not only functional but also economic, ergonomic, legal, and environmental. Therefore, a complete requirements gathering system should enable to collect all the information for those aspects. Gathering requirements from various sources is one of the functions of requirements management system. Classifying requirements and storing the requirements in a well-structured template are more useful to designers in product design process.

5.2 Types of product requirements in the product life cycle

Requirements can be classified into many types: functional, physical, structure, cost, performance, environmental, etc. In the present thesis, the author divides the requirements into three levels, product level, corporate level, and environment level.

5.2.1 Product level requirements

The product requirements at this level focus on the functionality of the product, which includes both the functional requirements and structural requirements.

First, the reason of a product to exist is that its functionalities meet customer's requirements. Functional requirements specify functional properties of a product. They present the interactions between a product and its environments. A designer usually introduces functional features to the product in response to functional requirements. The following is an example of the functional requirements: "The vacuum cleaner should have the power of 1600W"

In order to contribute to the functionalities, there must be some structural requirements. Structural requirements may be requirements about the composition of a product by its components in terms of certain topological arrangement among the components. For example, the customers may specify that the vacuum cleaner must have a flexible arm and multi-shadowing for different cleaning surface. Structural requirements may also be requirements about the form features of the product. For example, "the diameter of the arm is around 40cm so that users can handle it easily."

5.2.2 Corporate level requirements

The requirements at this level focus on the corporate requirements that reflect the needs of the corporation regarding the product. Just as the end-user imposes various expectations regarding function, corporate customers (or stakeholders) impose their expectations as well. The requirements from marketing, business environment, finance, and manufacturing belong to corporate requirements.

The purpose of a company to design and manufacture a product is to make profit. Financial requirements are the most important to a company, especially to stakeholders. Financial requirements not only give restriction on the cost of manufacturing the product but also constrain the cost of designing and assembling. They are reflected in the selection of materials (economical vs. luxury) and inclusion of features (simple vs. sophisticated). "The total cost of manufacturing the vacuum cleaner should be no more than $50" is an example of financial requirements.

The time to market is another requirement imposed by a company. How well a company does is often not just related to how good its products are but how quickly they are delivered to the market. Beating the competition in the market by just a few weeks may have a dramatic impact on the success of a new product. One of the biggest benefits from reaching the marketplace first is acquiring a large market share.

5.2.3 Environment level requirements

In many cases, the function of a product can be significantly enhanced by the inclusion of features that result in less waste and pollution during use throughout its operating life. This includes systems that reduce the need for resources during operation, such as energy conserving appliances, washing machines that use less water, and intelligent traffic control systems. For the environment level requirements, the designer should think in an entirely new perspective on engineering in general, with the underlying goal of meeting the complex material needs of society in sustainable harmony with the life-giving forces of our natural world. This philosophy differs from current practice in many ways. Many present methods of design and manufacturing are descended from a time when resources were plentiful, and the adverse environmental effects of new materials and high volume production were of incidental concern. Basically, the environment requirements include the requirements on materials selection, waste, pollution, and end products recycle.

5.3 A Taxonomy for product requirements

Requirements management is one of the key elements that must be addressed in the design process. Yet the representation and management of product requirements is problematic in the field of requirements engineering. Since requirements are often ambiguous, incomplete, and or redundant in a design project, it has been a lack of suitable tools for managing product requirements. One of the foundations for developing such a tools is to establish a taxonomy for product requirements.

Table 11 is a template for a taxonomy of product requirements. In Tables 12, the author presents the general description of the product requirements at each stage of the product lifecycle.

Table 11: Template for a representation of taxonomy for product requirements

Requirements classification →

Product life cycle ↓

	Product Level		Corporation Level		Environment Level	
	Function	Structure	Cost	Time	Material	Pollution
Design stage						
Manufacturing stage						
Distribution stage						
Usage stage						
Recycle Stage						

By analyzing the relations between the product and its environments, we can derive the requirements at each stage of product life cycle. We present them in Table 12.

Table 12: Taxonomy for product requirements

	Requirement	Product Level		Corporation level		Environment level	
		Function	Structure	Cost	Time	Material	Pollution
Design Stage	The designer has knowledge to design the product on time	√	√	√	√	√	√
	The functions of the product can meet the customer's requirements	√				√	
	The product can be used easily	√	√				
	The price can meet customer's requirements			√		√	
	The product can be design based on technology legally	√				√	√
	The product has no pollution problem to environments and customers					√	√
Manufacturing Stage	Parts can be manufactured by exited machine		√	√	√		
	Minimize number of parts		√	√	√	√	
	Use standard parts and processed		√	√	√	√	
	Parts weight, size conform to ergonomics, avoid heavy, sharp, too small, and too big parts	√	√	√	√	√	
	Design Multiple useful Parts	√			√		
	Design for assembly, self-orientation		√	√	√		
	Material is un harmful to workers during process	√				√	

	Selected material has good machinability	√		√	√	√	
	Minimize the manufacturing process and the area to be machined		√	√	√		
	The designed tolerance of parts can be achieved by existed process	√	√	√	√		
	Minimized the specific assembly tools		√	√	√		
	Designed process makes minimized pollution	√					√
	Specify the process can be done in the workshop	√		√	√		
	Designed processes avoid generating waste sand, wastewater, and other emissions, and are energy material efficient, and avoid defects		√	√	√	√	√
	Selected material has good feature to perform functionality	√				√	
	Avoid toxic or otherwise hazardous materials in the process	√				√	√
	Minimize depth and force of insertion	√	√	√	√		
Distribution Stage	Avoid too large size of package		√				
	The package is easy for handing by existed tools or hands		√		√		
	The label of package is clear	√					

	The package conforms to regulation	√	√			√	
	The package can protect the product and avoid the pollution to environments and humans		√				√
Usage Stage	Has good interface for operation	√	√			√	
	Avoid operation complexity	√	√	√	√		
	Clear labeling and manual for users		√		√		
	Avoid noise, vibration to harm users' health	√	√			√	
	Has good maintainability		√	√	√	√	
	Easy disassembly		√	√	√	√	
	Avoid heavy parts to be moved in maintenance		√	√	√	√	
	Has functionality to perform the job	√	√	√	√	√	
	Conform to Ergonomics	√	√		√	√	
	Avoid hazard power system	√	√		√	√	
	Has good reliability	√	√	√	√	√	
	Avoid specific maintenance tools		√	√	√	√	
	Avoid the pollution during operation	√				√	√
	Avoid using hazardous material during operation and maintenance	√		√		√	√
	Has good power system to perform the job	√	√			√	
	Has security system to avoid the injury to people	√	√				

	Has good interface with objects to be performed	√	√	√	√	√	
	Avoid hazard to operation environment	√				√	√
	Conform to standards	√	√			√	√
	Can be used in required environment	√				√	√
Recycle Stage	Conform to ergonomics		√				
	Avoid two small and two large parts	√	√			√	
	Minimize the number of parts		√			√	
	Avoid specific machine and tools during disassembly	√	√	√	√	√	
	Design reused parts	√		√	√	√	√
	Minimize the hazard of disposal parts to environments	√				√	√
	Clear the labeling of parts for disassembly		√		√		
	Avoid use complex machine and tools for disassembly		√	√	√	√	
	The form and structure design should conform to machine		√	√	√		
	All the disassembly process can be done in workshop		√	√	√	√	√
	Select recycle material	√		√	√	√	√

5.4 Summary

Despite all the efforts, the current design process often leads to the introduction of products that do not meet customer's expectations and corporate requirements, especially in the ever-increasingly competitive market. The major problems are how to capture the complete requirements from various resources and manage them in a proper way. In this section, the author first extracts the design requirements at each stage of the product life cycle according to the relations between the product and its environments. Second, the author proposed a taxonomy of product requirements for facilitating the classification of requirements, according to which product requirements are divided into product level, corporation level, and environment level.

Chapter 6 **Systematic Procedures for Development of Design Requirements**

Based on the ontological study of environments and its relations to product, the author proposes a systematic procedure for gathering product requirements in a design project. In this chapter, the steps in this systematic procedure are introduced. A case study is conducted to show how the model works in a new product design.

6.1 Systematic procedures for gathering product requirements

Extending the environment-based design theory (Zeng, 2004), the author develops a systematic model for requirements development in the design process.

Step 1: Identify product system

This process starts with a product design problem described by natural language. A formalization procedure will be applied to find the nouns, verbs, and their relations, which are further classified into product, environment, and their relationships. Linguistic analysis is the core of this process. The details are studied by Chen et al. (Chen et al., 2004). Denoting the identified product system by $\oplus\Omega_m$, we have

$$\oplus\Omega_m = \oplus(M^d \cup E)., \quad (15)$$

where M^d is the product and E is the environment in which the product works.

Step 2: Identify stages of the product life cycle

The concept of product life cycle is an effective and powerful methodological philosophy for obtaining the most satisfying product design requirements from an integrated and global viewpoint. The product to be manufactured is related to the product life cycle of manufacturing products, distributing products, using products, recycling products and so on. In product design, the conditions relating to each issue of the product life cycle, that is, the environmental conditions of the products, should be completely comprehended. The information about requirements should be obtained from all sources of the product life cycle. For an individual product, the process of each stage is different. For example, some product involves a coating process, while the other product involves a machining process. Clarifying the product life stages and identifying the process issue are the foundation of the model. By denoting the identified product life cycle by $\oplus L^S$, we have the following formula,

$$\oplus L^s = \bigcup_{s=1}^{5} L^s \quad . \tag{16}$$

Step 3: Identify implicit environments in each stage

The goal of a product design is to obtain design solutions that can satisfy customer's needs as much as possible. In order to reflect information about the actual manufacturing of products, the information analysis of needs and decision making of product designs are concurrently conducted. In terms of identified product and environment in Equation (15), we can derive the implicit environment components related to the design problems based on human, built, and natural environment for a product design. The output of this step will be the user of the product and the working environment at each stage of the product life cycle. The structure of the working environment is also analyzed in details. As a result, a product environment is updated and denoted by $e_i (i = 1...n)$. This is reflected in an updated product system:

$$\oplus(M^d)' = \oplus(M^d \cup (\bigcup_{i=1}^{n} e_i))\big|_{L^s} \quad s=1....5. \tag{17}$$

Step 4: Identify the relations between the product and its environments

As was pointed out in the theorem of the source of design requirements, all design requirements stem from product environment. Therefore, to gather product requirements, both the environment and product should be decomposed into basic pieces so that basic relations between product and environment can be identified. These basic relations are the foundation of design requirements.

$$\begin{aligned} M^d &= \bigcup_{i=0}^{k} m_i\big|_{L^s} \\ E' &= \bigcup_{j=0}^{n} e_j\big|_{L^s} \end{aligned} \quad s=1...5. \tag{18}$$

Substitute (18) into (17), we get:

$$\begin{aligned} \oplus(M^d)' = &(\bigcup_{i=0}^{k} \oplus m_i) \cup (\bigcup_{j=0}^{n} \oplus e_j) \cup \\ &(\bigcup_{i=0}^{k}\bigcup_{j=0}^{n} (m_i \otimes e_j) \cup (e_j \otimes m_i))\big|_{L^s} \end{aligned} \quad s=1....5. \tag{19}$$

Step 5: Extract design requirements and construct the requirements taxonomy

After the relations between the product and its environments are identified, the requirements can be extracted. Basically, the design requirements are implied in $\bigcup_{i=0}^{k}\bigcup_{j=0}^{n}((m_i \otimes e_j) \cup (e_j \otimes m_i))$ at each stage of the product life cycle. Finally, the requirements can be classified into the product level, the corporate level, and environment level.

The model is illustrated in Figure 23.

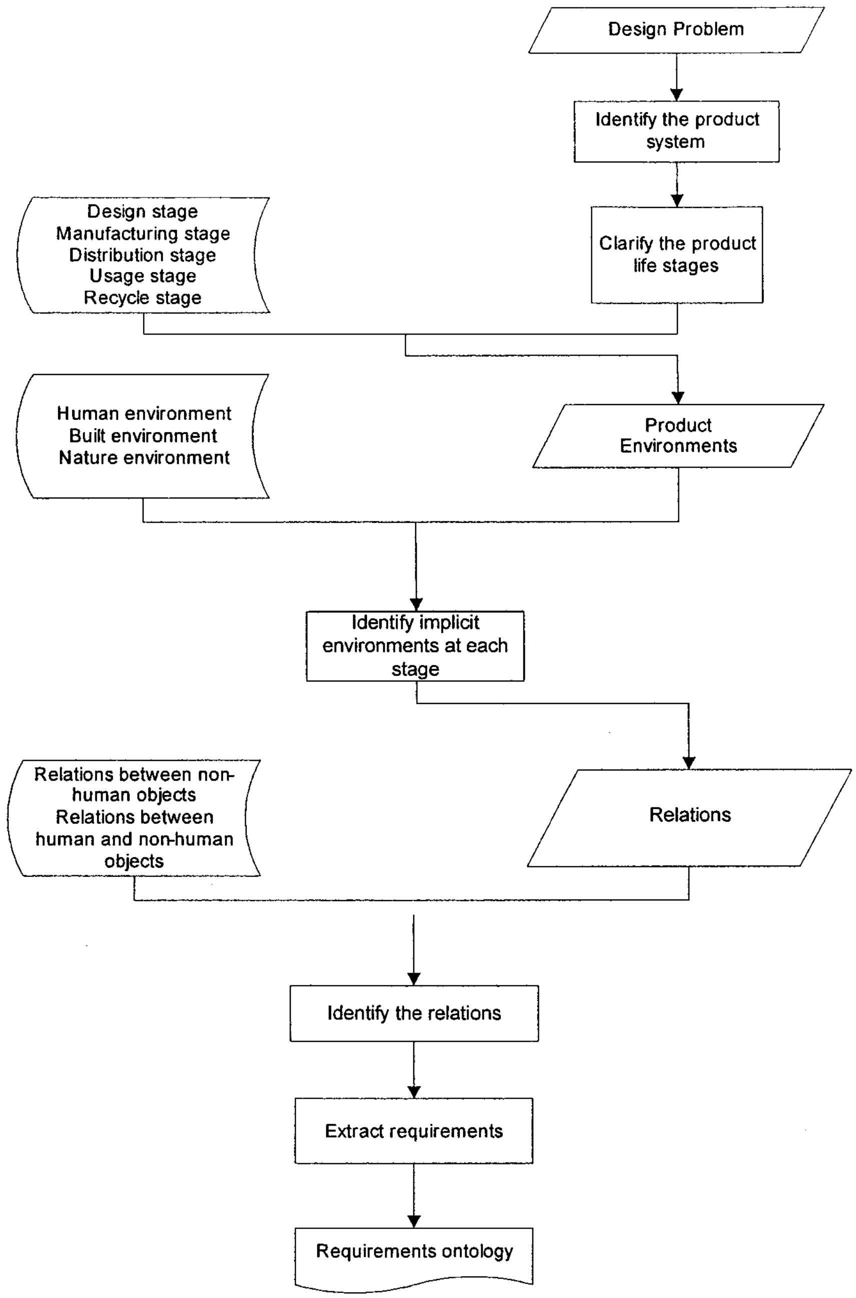


Figure 23: A systematic model

6.2 Case study

In this section, a new product is chosen as an example to show how the two sets of ontology are used in the systematic model to gather design requirements from the early stage of the conceptual design. The task is to design aquatic walking shoes that help people walk on the surface of water. The following is a description of the problem:

The aquatic walking shoes are used by people to walk on the surface of water. The shoes should not require additional power. They should be safe and reliable. Maintenance of the shoes should be easy.

The following shows the procedures proposed in this chapter for designing this product.

Step 1: Identify product system

From descriptions of design problem, it can be seen that there are only four sentences, which involves the following components:

- Shoes
- People (user)
- Water

The relationships between the components based on the description are illustrated in Figure 24.

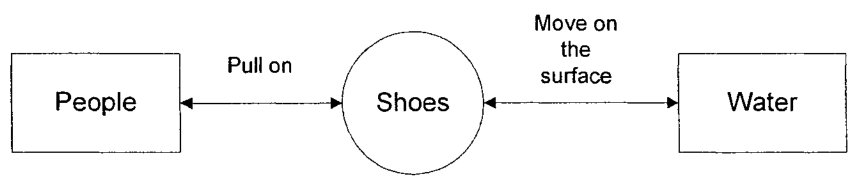


Figure 24: Relations between the components

Step 2: Identify stages of the product life cycle

The descriptions give us the requirements of our clients: the *aquatic walking shoes* are worn on feet. They should be safe, do not need additional power and can be easily controlled in its direction in any weather. If we analyze those requirements by the way of the product life cycle, they also involve five stages of product life cycle that we discuss in Chapter 3 including design, manufacturing, distribution, usage, and recycle stages. Considering the shoes for sport and amusement, we discuss only the stages more closely related to users. They are the usage stage, the transportation stage, and the assembly stage, which are illustrated in Figure 25.

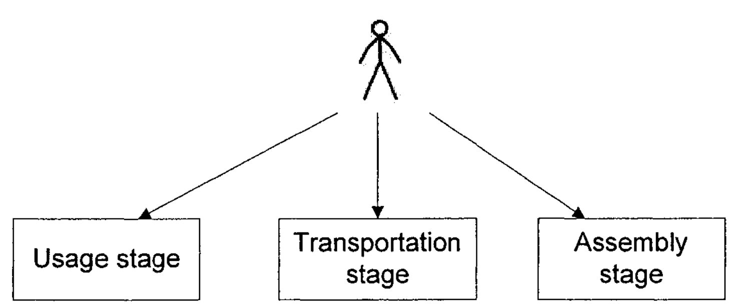


Figure 25: Stages of product life cycle

Step 3: Identify implicit environments in each stage

The description of the original requirements is not complex. It is, however, too vague and inadequate to allow further analysis. For example, what is the real mean of "*The shoes are safe on the water*"? Actually, it may mean that the structure is strong enough, or it may mean that shoes can provide enough buoyancy to ensure that people are safe on the water. Therefore, in order to specify the detailed requirements, we should analyze the environmental components that are related to the shoes within each stage of the product life cycle.

By using the ontology that the author discusses in Chapter 3 for identifying the environments of the shoes, we can get the environment components at each stage as follows:

Table 13: Environments in each stage

Stage	Environment
Usage stage	People
	Water
	Natural environment (Wind)
Transportation stage	People
	Transportation tools
Assembly	People
	Tools

Step 4: Identify the relations between the product and its environments

The product requirements come from the relations between a product and its environments. By analyzing the relationship, we can get more detailed requirements for product, particularly the function and the structure. Simultaneously, we can derive the components which can cooperate to conduct the operations. In this step, we analyze the relations between the product and its environments by using the ontology proposed in Chapter 4.

Usage stage: the previous paragraph mentions that the major environments of the *aquatic walking shoes* (Denoted by S_0) in usage stage are people, water, and wind. Table 14 summarizes the relations between them and other components.

Table 14: Relations in usage stage

Environment	Relation	Form		Factor	Component
Shoes-people	Physical relation	Wear	Containment	Ergonomic	Shoe groove
		Operation	Drive	Interface, force	Transmission system
Shoes-water	Directly dynamic relation	Float	Float	Buoyancy	Buoy
		Movement	Move	Advance power	Screw
Wind-people	Physical relation	Retardance		Resistance	Overall
Wind- shoes	Directly dynamic relation	Retardance		Resistance	Overall

Overall design

There are two main problems that need to be dealt with. One is how to deal with the problem of float on the surface of water; the other is how to drive the shoes to move. Figure 26 and Figure 27 give us the force relations between them.

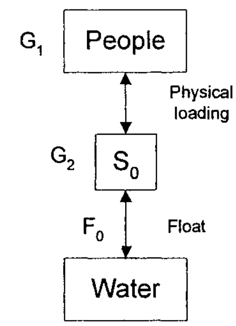


Figure 26: Force relations

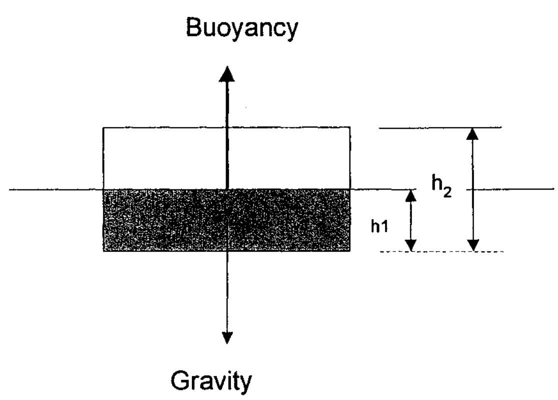
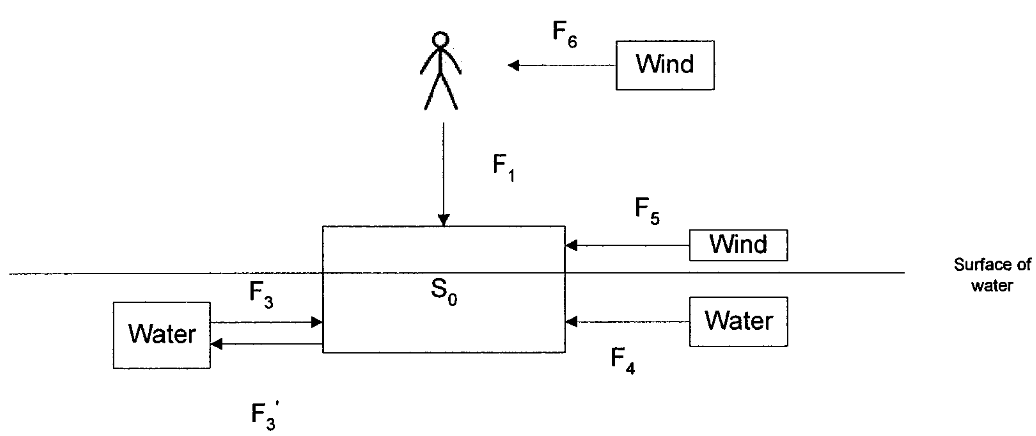


Figure 27: Principle of Buoyancy

Suppose the weight of person is $G_1 = 800N$ and the weight of the shoes is $G_2 = 200N$, the buoyancy force F_0 should be equal to G_1 plus G_2. At the same time, the buoyancy force is proportional to the volume of liquid that the shoes displace the force of gravity and the density of the liquid: $F_0 = \rho_{water} gV$. The volume of the shoes can not be less than 0.1 m^3. One shoe is not less than 0.05 m^3. According to basic buoyancy principle, the average density of the shoes material (ρ_0) has to be less than that of water (ρ_2).

Weight of person(G_1)	*800N*

Weight of shoes(G_2)	*200N*
Buoyancy force ($F_0 = G_1 + G_2$)	*1000N*
Volume of the shoes	$\geq 0.1 m^3$
One piece of the shoe	$\geq 0.05\ m^3$
Relation of density of shoes	$\rho_0 < \rho_2$
Relation of structure of shoes with gravity	$Volume = \frac{G_1 + G_2}{\rho_{water} g}$



F_1: The force from people to shoes
F_3: Thrust force of water to shoes
F_4: The resistance of water to shoes
F_5: The resistance of wind to shoes
F_6: The resistance of wind to people

Figure 28: Relations between the shoes and its environments

In order to move forward, the relations of the force must satisfy $F_3 > F_4 + F_5 + F_6$. F_3 bases on the design concept of the transmission system. The transmission system translates the vertical force F_1 to advance power F_3, and $F_3 = f(F_1)$. The function $f(F_1)$ is based on the transmission design, which is discussed in part design later. F_4 is based on the shape of submerged part of shoes. F_5 is based on the shape of the part of the shoes over water. F_6 is related to the weather. In general, a streamline design is advantageous to reduce water resistance.

Part design

After analyzing the relations between the *aquatic walking shoes* and their environments, we obtain four components:

- S_1: Shoe groove. Its function is to provide people enough space in which people may put their feet.
- S_2: Transmission system. Its task is to convert the energy from people to the rotating force.
- S_3: Screw: its role is to produce the advancing power from the action and reaction of the water force.
- S_4: Buoy: its job is to provide a space to install all the sub-systems and ensure the enough buoyancy.

Figure 29 shows us the overall function and structure.

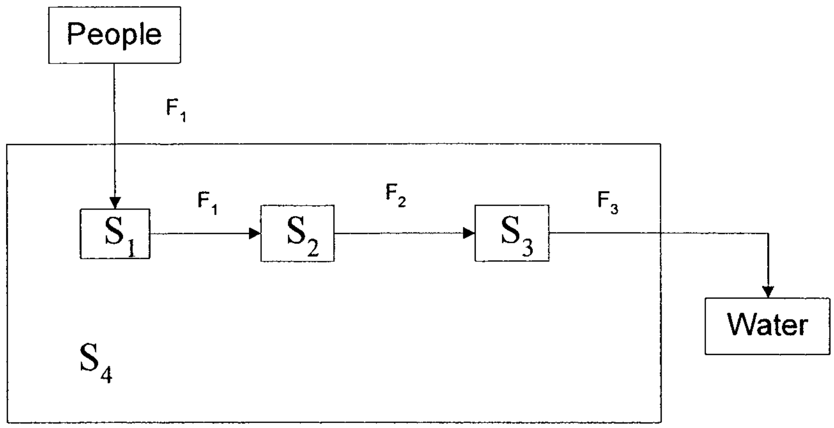


Figure 29: Overall structure of the system

For each individual part, we can use same method to study the requirements by identifying their environment components and relationships. The following figures present the environmental components and relationships between the shoe groove, the transmission system, and the screw, etc.

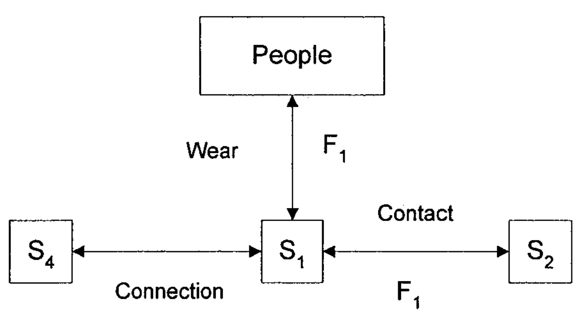


Figure 30: Relations between the shoe groove and its environments

The shoe groove gives a space to person who pulls on the aquatic walking shoes and applies forces on the transmission system. The shoe groove should be suitable for the size of the user's foot. The shoes must be comfortable and move with no trouble. The size and geometry of the shoe groove should conform to ergonomic factors. The relations between the shoe groove and the buoy is a connection relation. The shoe groove should be riveted to the buoy. The shoe groove should allow the transfer of the strength of person to the transmission system. The shoe groove ensures that people's feet can be perfectly riveted and effectively apply force to the surface of the transmission system.

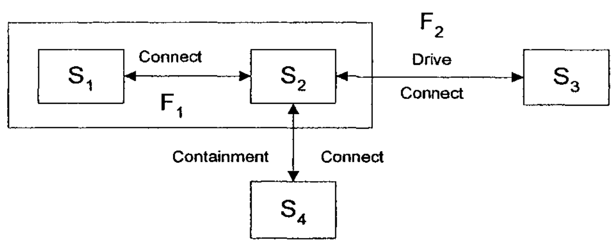


Figure 31: Relations between the transmission system and its environments

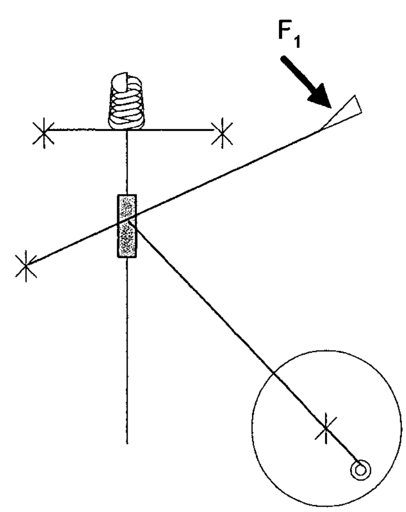


Figure 32: Example of the transmission system design concept

The environments of the transmission system are the shoe groove, the buoy, and the screw. The relationships between the transmission system and the buoy are containment and connection. They require that the transmission system fit easily in the buoy and be riveted to the buoy. The transmission system and the screw must translate the reciprocating motion into rotary motion and drive the screw rotating. $F_3 = f(F_1)$. The function $f(F_1)$ is based on the transmission design. An example of design concept of the transmission system is illustrated in Figure 32.

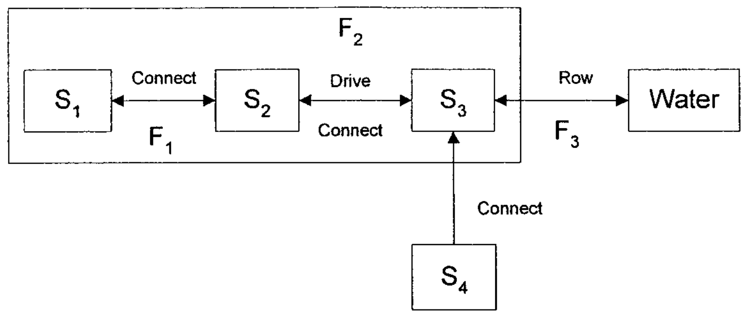


Figure 33: Relations between the screw and its environments

The environments of screw are the transmission system, the water, and the buoy. The relation between the screw and the transmission system is discussed in the section dealing with the transmission design. The relationship between the screw and the water is to produce advance power by rotating in the water. The relation between the screw and the buoy is a connection relation. The screw should be riveted to the buoy.

Transportation stage: the key consideration in transportation stage is that people can carry the shoes easily by using the transportation tools. The environments of the shoes in this stage are people and the transportation tools (we suppose it is a car in this case).

Table 15: Relations in transportation stage

Environment	Relation	Form	Factor	Component
People - shoes	Physical relation	Movement	Weight, size	Handle
Transportation tool (car)	Directly static relation	Containment	Geometry	Overall

The relation between people and the shoes in the transportation stage is to take up the shoes to the site. It belongs to a physical relation in the ontology. The form is movement. The considered factors are the weight and size of the shoes. A handle should be designed for carrying the shoes. Another environment in the transportation stage is the tools that people use to transport the shoes. Suppose the tool is a car, the shoes should fit easily into the car.

Assembly stage: the major environment of the shoes in the assembly stage is the people and the tools that people use to assemble the shoes.

Table 16: Relations in assembly stage

Environment	Relation	Form	Factor	Component
People - shoes	Physical relation	Assembly	Geometry, joint point structure	Each part
Tool - shoes	Directly static relation	Interaction	Interface	Each part

In order to assemble the shoes easily, the parts are easy to assemble. The parts are self-oriented, and the joint point of the parts is easy to assemble by using the existing tools. The structure of parts should conform to human factors.

Step 5: Extract design requirements and construct the requirements taxonomy

According to the analysis of relations between the shoes and their environments and relations between the parts, we can extract the requirements of the aquatic walking shoes.

Table 17: Requirements of the shoes

Requirement	Product Level		Corporation level		Environment level	
	Function	Structure	Cost	Time	Material	Pollution
The shape of the shoes is a streamline design.		√			√	
The structure of the shoes is ergonomic.		√			√	
The shoes design is symmetrical.		√				
The volume of the shoes conforms to $Volume = \frac{G1 + G2}{\rho_{water} g}$	√	√	√		√	
The density of the shoes material is less than density of the water. $\rho < \rho_{water}$			√		√	
Advance power is bigger than resistance of water. F3>F4+ F5+F6	√	√	√	√		
The size of the shoe groove conforms to human factors		√				
The shoe groove ensures that people's feet can be perfectly riveted and that people effectively work on the surface of transmission system.	√	√				
The structure of transmission system is fit for installing in the buoy.	√	√		√	√	
The transmission is easily riveted with the buoy.	√	√		√	√	
The transmission system has good intensity for transferring power.	√				√	
The transmission can translate the reciprocating motion to rotary motion effectively and efficiently.	√	√				
The screw design conforms to fluid principles.	√	√		√	√	
The shoes can put into a car easily		√	√	√		
The shoes have an ergonomic handle for pick up		√		√		
The parts are self-oriented.		√	√	√		

Summary: obviously, the original requirements are too vague and inadequate. The information is limited. By using two sets of ontology and following the systematic procedure, the designers can get more detailed requirements behind the original description.

Chapter 7 **Concluding Remarks**

7.1 Conclusions

The issue facing designers and design organizations is how to obtain correct requirements. In order to achieve a quality design, customer's requirements should be understood and identified before a designer attempt to construct the conceptual design, especially in the case of a new product design. Since there has been a lack of a robust requirements management system to help designers to get the right requirements at the right time, a systematic approach for gathering product requirements is essential. As an extension of the environment-based design theory (Zeng, 2004), the present study has developed two sets of ontology for the systematic gathering of product requirements. First, the ontology is developed for product environments based on product life cycle in Chapter 3. Second, the ontology for product-environment relations is developed to identify the relations between product and its environment in Chapter 4. By using these two sets of ontology, a taxonomy for product requirements is developed to classify the requirements into three levels: product, corporate, and environment level. By combining the ontology and taxonomy together, a systematic procedure for gathering product requirements is proposed in Chapter 6.

The following summarizes the major contributions of the present thesis:

First, by using environment-based design theory and the concept of concurrent engineering, the author gives a detailed explanation of how to take into account the factors throughout a product life cycle, which includes the design stage, the manufacturing stage, the distribution stage, the usage stage, and the recycle stage. The factors considered in a design program should be thought over throughout each stage. In Chapter 3, the author analyzes the process at each stage and develops an ontology to identify the environment components based on the product life cycle. This ontology solves the problem 1: how to identify the environment component based on the product life cycle.

Second, requirements are derived from the relations between a product and its environments in which the product is expected to work (Zeng, 2004). In Chapter 4, the author develops an ontology to describe the relationships of objects in the universe. The relationships include the relations between non-human objects and the relations between non-human objects and human. By using this ontology, the relations between the product and it environments are identified. This ontology solves the problem 2: how to identify the relations between the product and its environment.

Third, since the requirements are complex and comprehensive, in Chapter 5, the author develops the requirement taxonomy to help designers manage the requirements. For the various purposes of different levels of managements, the requirements are classified into the product level, the corporate level, and the environment level. The product level requirements include functional requirements and structural requirements. Not meeting the product level requirements, there is no reason for the product to exist. The corporate level requirements include cost and time requirements. Meeting those requirements helps the company make a profit. The environment level requirements involve the material selection and pollution during the product manufacturing and use. Meeting those requirements helps the company take charge of its social responsibility.

Fourthly, the author proposes a systematic procedure for gathering product requirements, especially for a new product design. A case study, a design of aquatic walking shoes, demonstrates the effectiveness of the systematic procedure. This is a new product design problem. Starting from the original description of the product given by customers, the author analyzes the environment components and relations between the product and its environments by following the systematic procedure. At the end, more specific and detailed requirements are extracted. A concept is generated for showing the effectiveness of the methods.

7.2 Recommendation for further research

This research is a preliminary study of ontology for requirements management. The author investigates traditional engineering sciences and develops a preliminary ontology to be used for gathering product requirements. There are a number of possibilities for its further investigation.

First, ontological relations between objects in the universe need to be researched consistently. Although relations between objects have been discussed in the thesis, this is a preliminary study. The ontology is not comprehensive enough for understanding all the known existing natural laws and effects due to their complex and diverse forms.

Second, the qualitative requirements are not sufficient for designers to process the detailed design. How to transfer the qualitative requirements into quantitative specifications is an important research topic. In such further research, developing the parameters related to the requirements would be useful for designers during the creation of the detailed design. Moreover, the relationship between the requirements should be further investigated, since the requirements may be mutually related and interdependent. In some cases, the requirements may conflict with each other. Developing a priority system helps a designer take a decision when faced with any conflicts.

Finally, the systematic procedure presented in the present thesis is one part of a larger ongoing system. This system attempts to provide industry designers with a robust computer-aided product development tool. This system is based on Dr. Zeng's design theory: environment-based design theory, which involves linguistic analysis, requirements analysis, and a sketching system. The procedures proposed in this thesis will be integrated into the on-going conceptual design tool to help industry designers implement a design throughout all stages from collecting product requirements to creating rough concepts.

Publication

Publications in Referred Journal

M. Chen, Z. Chen, L. Kong, and Y. Zeng, 2005,"Gathering and classification of product requirements for medical devices design", Transactions of the SDPS: Journal of Integrated Design & Process Science, Vol. 9, No. 4, pp.61-70, 2005

M. Chen and Y Zeng, "Preliminary study of ontology for systematic gathering of product requirements". In preparation

Publications in Referred Conference

M. Chen, Z. Chen, L. Kong, and Y. Zeng, 2005, "Gathering and classification of product requirements for medical devices design", The Ninth World Conference on Integrated Design & Process Technology, Beijing, China, June 12-17, 2005

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