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Design for Product Adaptability

by

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Abstract

Adaptable design (AD) is a new design approach for efficient and effective product design considering functionality, manufacturing efforts, customization and environment friendliness. Adaptable design aims at developing designs and products that are adaptable to various circumstances. In this context, this thesis mainly discusses how to achieve product adaptability and evaluate the design candidates. This research introduces a detailed methodology of design for improving product adaptability. The various phases in adaptable product design, including function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation and detail design, are identified in this research. The details of design activities in each of the adaptable design phases have been developed. A new method to evaluate design candidates in adaptable design process has also been developed by using the grey relational analysis approach to integrate the different evaluation measures for prioritizing different design candidates with different fundamental and adaptable functions. Two case studies are conducted based on the introduced design methodology and design process on how to achieve the product adaptability.
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Dedication

I would like to dedicate this thesis to my parents Yingchuan Li and Zhimin Du.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

With the intensive competition in the global market, new products with better functionality, quality, features, customization, environmental friendliness, lower cost and short product development lead-time need to be manufactured for firms in order to stay competitive. Many advanced design and manufacturing technologies have been developed and employed for improving competitiveness of the products. It has been recognized that conceptual design has major impact on most issues in the competition. Advanced conceptual design technologies are required at early product development stage to make decisions considering the functionality, quality, features, customization, environmental performance and cost of the products.

In the past two decades, considerable research progresses have been achieved on the development of fundamental design theory and methodologies, as well as effective tools, for helping design engineers at the early conceptual design stage. Suh developed an axiomatic design approach by maintaining the independence between functional requirements (FRs) and design parameters (DPs) (Suh, 1990, 2001). Pahl and Beitz introduced methods for modeling functions and function-based design (Pahl, 1988). Ulrich discussed the design of product family/portfolio using modular and platform design approaches (Ulrich, 1995). Simpson et al. (Simpson, 2001) and Newcomb et al. (Newcomb, 1996) have also achieved considerable research results on modular design and platform design in the past years.
In recent years, a new design approach namely adaptable design (AD) for efficient and effective product design considering functionality, manufacturing efforts, customization and environment friendliness was introduced (Gu, 2004). Adaptable design aims at developing designs/products that are adaptable to various circumstances. In this context, this thesis mainly discusses how to achieve product adaptability and evaluate the design candidates. The goal of this research is to develop a design methodology for product adaptability and a method to evaluate and prioritize design candidates created in adaptable design.

1.2 Concept of Adaptable Design

Adaptable design is a design paradigm for both economical and environmental benefits. The underlying philosophy of adaptable design is the ability of product to adapt to new requirements and the reuse of a product and design when requirements are changed. Adaptable design is conducted through replacement of multiple products by one adaptable product with a set of add-on accessories and/or attachments (Gu, 2004).

In the general design process, adaptable design can result in the description of a product that, when materialized according to this description, can fulfill a required set of adaptability functions. This description can be in the forms of blueprints, instructions, CAD models, prototypes, etc. Therefore, the design process and subsequent production result in the creation of two entities: a design and a product (Gu, 2004). Figure 1.1 shows the process and results of adaptable design.
In previous research, the adaptability in adaptable design was categorized into design adaptability and product adaptability depending on which aspect is the subject of adaptation (Gu, 2004). A design with design adaptability can be changed by the manufacturer to generate the modified design to produce a variety of new products. After the adaptation which is performed by the user in a usually reversible and simple procedure, the product with product adaptability can be changed into the modified product to provide different functions or usages.

Design adaptability helps the manufacturer reuse the existing design and manufacturing equipment, which will cost less than to create new designs and to reconfigure the manufacturing equipment. Product adaptability allows the user to utilize the same product under different conditions, by replacing different functional parts or upgrading current parts. Both design and product adaptabilities are also beneficial to the environment because they can reduce the total production volumes and extend the products' life spans.
1.3  Problem Statement

The goal of this research is to develop a methodology of the design considering product adaptability and a method to evaluate and prioritize design candidates created in adaptable design. The design methodology for product adaptability is an attempt to establish a procedure that will achieve product adaptability for the use of modules based on a functional structure of the product. Product adaptability has many benefits for manufacturers and customers, such as increased product versatility, decreased development lead time and costs, improved customizability and functionality of product.

A quantitative evaluation method is used to prioritize design candidates. In order to reduce the part cost and assembly cost, and improve product operationability and the product adaptability, it is necessary to select the most appropriate design candidate at a conceptual design stage. Due to the different architectures in diverse design candidates, the physical modules that provide different functions and the interfaces among different modules are usually different. Therefore, evaluation of the different design candidates with different architectures is required for selecting the best design candidate.

1.4  Thesis Overview

In the previous research, the adaptability in adaptable design was defined by design adaptability and product adaptability (Gu, 2004). This thesis mainly focuses on product adaptability. In Chapter 3, product adaptability is defined by specific product adaptabilities and general product adaptabilities. Specific product adaptabilities include
extendibility of functions, upgradeability of modules, and customizability of components. The measures of specific product adaptabilities are discussed in details in Chapter 3.

This thesis also presents the detailed methodology of design for improving product adaptability. The various phases in adaptable product design, including function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation and detail design, are identified in this research. The details of design activities in each of the adaptable design phases have also been developed. This method will be discussed in detail in Chapter 4.

A new method to evaluate design candidates in adaptable design is introduced in this research using the grey relational analysis approach. The grey relational analysis approach (Sih, 1997) is employed in this research to integrate the different evaluation measures for prioritizing different design candidates with different fundamental and adaptable functions. These design candidates are evaluated by different life-cycle evaluation measures including specific product adaptability of design, part and assembly costs of manufacturing, operation ability by customers, etc., as discussed in Chapter 5.

At last, two case studies which are both designed according to the introduced design methodology and design process on how to achieve the product adaptability are presented to illustrate the design method discussed in Chapter 4. The second case study is also used to demonstrate the effectiveness of evaluation method given in Chapter 5.
1.5 Organization of This Thesis

Chapter 2 gives a literature review on engineering design and adaptable design. Chapter 3 discusses the product adaptability in adaptable design and introduces the method for measuring specific product adaptability. Chapter 4 presents the methodology of design considering product adaptability. It includes the design goals, guidelines and design processes. Chapter 5 introduces the method to evaluate and prioritize design candidates created using the developed design methods and design processes. Chapter 6 provides two case studies to illustrate the effectiveness of the introduced methods for designing and evaluating design candidates with product adaptability. Chapter 7 gives conclusions and future work of this research.

1.6 Terms and Definitions

Product Adaptability

Product adaptability refers to the ability of a product to be adapted to various usages or capabilities. The adaptation task is usually performed by the users when they want to modify the product to deliver various functions or to enhance its performance. For example, Figure 1.2 shows an upright vacuum that is also used as a hand vacuum. This design provides product adaptability to extend the utility of the vacuum and enable the user to replace two products with one. Since this adaptation is reversible and the alternation between two usages happens very frequently, the design of this vacuum has made this adaptation easy to be performed by the user.
Product adaptabilities are classified into specific product adaptabilities and general product adaptabilities depending on whether predicted information for specific adaptations is available.

**Specific Product Adaptability**

A product can be identified with fundamental functions and adaptable functions by the planned information at the concept design stage, and then be designed to accommodate the product adaptabilities. Such product adaptability is called “specific product adaptability”. For example, Swiss army knife is an adaptable product with more than ten specific product adaptibilities including the different functions of knives, scissors, screwdriver, hook and so on to satisfy various customer requirements which are identified at the conceptual design stage.
General Product Adaptability

Although the product is not designed for the planned adaptation, it is still applicable to this adaptation without targeting specific adaptabilities. Such product adaptability is called "general product adaptability". For example, the LEGO toy system is a typical product with general product adaptability. By using LEGO bricks, the user can successfully build different models which are not specifically defined at the concept design stage.
CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The adaptable design approach considering product adaptability was introduced based on the results achieved from previous research on design theories and methodologies. In this chapter, these relevant design theories and methodologies are introduced. Most of the relevant researches focus on design of flexible product configurations such as development of product platforms or development of modular products. The goal of adaptable design is to further improve the product configurations that allow new features and functionalities to be added to products in the future. The underlying philosophy of adaptable design is the ability of product to adapt to new requirements and the reuse of a product and design when requirements are changed.

In the rest of this chapter, Section 2.2 introduces the axiomatic design approach which is used for establishing the functional structure of the design and mapping the design functions to design solutions. Section 2.3 gives a review of the research on product configuration design, including product architecture modeling, modular design, and platform design. Section 2.4 reviews the previous research on adaptable design, including the concept of adaptability and methods for assessing the adaptability. Section 2.5 explains a number of design evaluation methods to help design engineers select the design from multiple design candidates through design evaluation.
2.2 Axiomatic Design

During the design process of adaptable design, the functions of the design need to be first identified. These functions are usually organized in a certain data structure (Gu, 2004). The goal of adaptable design is to extend the function of the products at the operation stage. Since the function decomposition method in the axiomatic design approach (Suh, 2001) is employed in this research for developing the design process model, the axiomatic design approach is introduced in this section.

Axiomatic design method provides a framework for modeling various design functions, design solutions, and relations between design functions and design solutions at different levels (Suh, 2001).

A design is usually started by defining the objectives and requirements. These objectives and requirements are modeled in the functional domain in axiomatic design, while the physical solutions are modeled in the physical domain. In axiomatic design, these two domains are linked by their relations. The functional domain is described by functional requirements (FRs), while the physical domain is described by design parameters (DPs). The design process associates the FRs in the functional domain to the DPs in the physical domain through zigzagging mapping. Design axioms provide principles to identify the designs with good quality.

The major concepts used in axiomatic design include:

1. Domains, which separate the functional descriptions and physical descriptions of the design.
(2) Hierarchies, which categorize the progress of a design in the functional and physical domains from the abstract level to more detailed levels. According to the hierarchies, the lower-level design decisions are consistent with the highest-level design intent.

(3) Zigzagging, which indicates that the decisions made at one level of the hierarchy affect the problem statement at lower levels of the hierarchy. In zigzagging process, the design is initiated from functional domain to physical domain to conceptualize a design and determine a DP that corresponds to the FR. Once a DP is chosen, the children level FRs, e.g., FR1 and FR2 in Figure 2.1, could be created in the functional domain. Then in the physical domain, DP1 and DP2 can be determined to satisfy FR1 and FR2, respectively. This zigzagging process is continued until the highest-level FR can be satisfied without further decomposition. Figure 2.1 shows the hierarchies of functional requirements (FRs) and design parameters (DPs), and the zigzagging process.

Figure 2.1: The FR and DP hierarchies and zigzagging process (Suh, 2001)
(4) Design Axioms, which require that the independence of the functional requirements must be maintained, and the information content (i.e., cost, complexity, etc.) must be minimized, in order to generate a design with good quality.

Suh also introduced the design matrix to associate the FRs and DPs in the design hierarchy. FRs, DPs, and their relations are defined by:

\[ \{FR\} = [A]\{DP\} \]  

(2.1)

where:

\( \{FR\} \) = a vector of the functional requirements in the functional domain

\([A]\) = a design matrix associating the functional domain and the physical domain

\( \{DP\} \) = a vector of the design parameters in the physical domain

When the design matrix \([A]\) is diagonal, each of the FRs can be satisfied independently by its respective DP. Such a design matrix indicates that the design is an uncoupled design. When the design matrix \([A]\) is triangular, the independence of FRs can be satisfied if the DPs are determined in a proper sequence. Such a design matrix indicates decoupled design. Any other form of the design matrix is called the full matrix which means the design is a coupled design.

The uncoupled design and decoupled design satisfy the independence axiom. Since components and modules need to be changed in an adaptable product, these components and modules of the product should be made as independent as possible. By using the axiomatic design as a guideline, the product can be designed to satisfy the independence axiom for improving the design/product adaptability.
2.3 Review of Research on Product Configuration Design

Product configuration design is a process to determine the product architecture and select proper components to meet the design requirements. Product configuration design serves as a link between concept design and detail design in the design process.

Product configuration is defined by a layout of components selected to satisfy design requirements. Different design configurations can satisfy the needs of different customers. For instance, the design of screwdriver with changeable bits can better satisfy the requirements of customers whose major concern is the space to store the tools than regular screwdriver set with screwdrivers of different types and sizes.

Some methodologies, such as modular and platform design, have been developed to provide better design configurations to satisfy the different requirements of various customers (Gershenson, 2004). The concept of product architecture was introduced in the research of product configuration design. Since adaptable design was introduced based upon the methods of modular design, platform design, interface design, etc., these methods are also provided in this section.

2.3.1 Product Architecture

The product architecture is created by using physical building blocks based on the functional requirements (Ulrich, 2004). Development of product architecture is started from the gathering of customer needs and mapping these needs to a functional model of the product. Pahl and Beitz concluded that the product architecture includes the layout of physical subsystems, their embodiments, and the overall shape of the product (Pahl,
Ulrich defined that the product architecture is composed of: (1) the arrangement of functional requirements; (2) the mapping from functional requirements to physical components; and (3) the specification of the interfaces among interacting physical components (Ulrich, 1995).

Product layout design is an important issue in product architecture design. The different architectures can influence the performance and costs of the product. Ulrich classified product architectures into the following 2 categories: modular architecture and integral architecture. Modular architecture is composed of physical product sub-structures that have one-to-one mapping between functional requirements to physical modules and decoupled interfaces among them. An integral architecture is composed of physical product sub-structures that have complex mapping from functional elements to physical components and/or coupled interfaces between components (Ulrich, 1995). The key measurement of product architecture is its modularity (Gershenson, 2003), the degree to which it is modular or integral. Modularity is a relative measure in evaluating product architecture, because products are rarely strictly modular or integral.

The overall goal of product architecture design is to determine product layouts to satisfy the customer needs. The end result of product architecture design is to achieve a rough geometric layout of product, descriptions of major modules, and documentation of the key interactions among the modules (Ulrich, 2004). To establish such product architecture, some methods were introduced for structuring the decision processes.

Ulrich recommended a four-step method to establish the product architecture (Ulrich, 1988).
The product architecture design is started by modeling function hierarchies. The first step is to create a schematic of the product. The schematic is a diagram representing the main function elements of the product. At this step, alternative structures should be developed. Commonalities in the structures are identified as shared elements. After creating one or more structures, the next step is to group the elements into modules. Some guidelines for clustering functions into modules are applied iteratively throughout this step. When suitable modules have been chosen, the next step is to create rough geometric layouts of the product. Some guidelines are also used iteratively to create the layouts. The last step is to identify the interactions and boundaries among modules. Material flows, energy flows, signal flows and module boundaries are investigated at this step. The three types of flows are used to define the interactions. The boundaries are used to define the interfaces among modules. In this thesis, this four-step method is adopted to establish the product architecture during the design process for achieving product adaptability.

Otto developed another method to establish product architecture (Otto, 2001). This method first organizes a function structure into a proper form for identification of all possible modules, and then provides heuristics for selecting modules. The last step is to generate layouts based on the identified modules.

2.3.2 Modular Design

In engineering design, modular design is a design methodology that aims at developing a product architecture consisting of discrete sub-systems in order to achieve a set of
perceived benefits (Gu, 1999). A module is defined as a component or a group of components that can be disassembled from the product non-destructively as a unit which provides a unique basic necessary function for the product to operate as desired. Modularity was defined as the degree to which product architecture is composed of modules with minimal interactions between modules (Allen, 1998).

A modular product is composed of distinct modules, so that these modules can be designed, manufactured and assembled separately. The module can be easily disassembled from the rest of the product for upgrading, repairing, recycling or reusing. The module may also be used in other products with the same interface to perform its given function. The modular product gives designers and users more flexibility to meet any changing requirements. Ali and Saed identified some advantages of modular design, including shorter lead time in product development, greater opportunity for customization and upgrades, lower cost due to amortization, better quality and design standardization (Ali, 2002).

Various methods of generating the modular products to fulfill the above advantages have been developed by researchers in the past decade. Gersheson et al. summarized the recently existing modular design methods into four main categories: checklist methods, design rules, matrix manipulations, and step-by-step measure and re-design methods (Gersheson, 2004).

Stone et al. described a heuristic method to identify modules for product architectures (Stone, 2000). Using a functional structure diagram, they first defined the material,
energy and signal flows and formed a functional structure by sub-functions. Then they used the functional structure diagram to identify three heuristics: (1) dominant flows, a set of sub-functions a flow passes through from system entry/flow initiation to system exit/flow conversion; (2) branching flows, a set of sub-functions making a parallel function chain associated with a branched flow; (3) conversion-transmission flows, a set of sub-functions responsible for the transition between flows. Each of these flows is a potential module. The material, energy and signal flows are used to identify dependencies between modules. The three heuristic methods provide a systematic approach to identify modules of product from a functional model.

Gu and Sosale presented a multi-objective optimization method for the clustering of modules for diverse life cycle objectives (Gu, 1999). In this approach, they developed a system that uses the relative precedence operations based on matrix methods to determine relative degrees between all the individual components. This methodology is used to first identify the relevant factors related to the design objectives, associate these factors to design components through interaction analysis, and then cluster components into modules.

2.3.3 Platform Design

In order to improve customization for intensive competition in the global market, many companies are using product families and platform design methods to increase variety and functionality, reduce cost and shorten product development lead-time. The platform design can offer flexible functions either by adding, removing, or substituting one or
more modules to/from the platform or by scaling the platform to target specific markets (Simpson, 2003).

A product platform can be defined as a set of common parts, components, and modules from which a family of derivative products can be efficiently developed and launched (Meyer, 1997). Simpson et al. classified platforms into the following categories (Simpson, 2001): (1) Process and manufacturing platforms. In this case the platform is not very integrated with the design of a product family. It is integrated into the process of how the products are manufactured. (2) Component standard platforms. This type platform unifies manufacturing issues in multiple products by using common components whenever possible. (3) Modular platforms. This type of platform uses modules for several products, so that common parts are used whenever possible. In some cases, one single product will contain multiple types of platforms.

Many advantages of platform design have been identified. The platform design methods are used for providing sufficient variety for the market while maintaining economies of scale within manufacturing processes of products, reducing development time and system complexity, reducing development and production costs, reducing costs resulted by customization, eliminating duplicated effort for producing components with similar functions, and improving ability to upgrade products. Platform design can also be used to reduce testing efforts of products (Roberson, 1998).

In the past decade, the methods and guidelines for development of platforms have progressed rapidly. Siddque and Rosen developed a Product Family Reasoning System,
which helps in platform and product family development (Siddque, 2000). During product platform design, designers must balance the commonality of the products in the family with the variety of individual products in the family. Many indices have also been developed to measure the commonality (Collier, 1981; Jiao, 2000; Kota, 2000).

Various optimization methods have also been developed in engineering design to help determine the best design variables for the product platform and individual products within the family. Fujita concluded that product variety optimization can be conducted through 3 steps: attribute assignment, module combination, and simultaneous design of both. Also an optimization method is provided for identifying the best design from the product family (Fujita, 2002).

Product families based on well-designed platforms have been successfully used to provide large numbers of product variants to target many different market segments. For example, Sony has used three platforms to support many different portable stereo products in its Walkman line.

2.4 Review of Research on Adaptable Design

In recent years, a new approach of product design, namely adaptable design (AD), for efficient and effective product design considering functionality, manufacturing efforts, customization and environment friendliness was introduced (Gu, 2004).

Adaptable design is a design paradigm for both economical and environmental benefits.
The underlying philosophy of adaptable design is the ability of product to adapt to new requirements and the reuse of a product and design when requirements are changed. Adaptable design is conducted through replacement of multiple products by one adaptable product with a set of add-on accessories and/or attachments. Three key elements need to be addressed in adaptable design: independence of functions, evaluation of adaptability, and a process of adaptive design based upon functions of the product (Gu, 2004).

Adaptable design is different from modular design, although modularization is primarily used in adaptable design for increasing adaptability. Adaptable design can provide: (1) segregated architecture of the product which can be reconfigured without breaking it into its constituent subsystems; (2) extra features and functionalities in a design for possible future needs; (3) compatibility among subsystems through standardization and generic forms of interfaces. Both adaptable design and modular design use modularization for upgrading and customization.

Hashemian and Gu established the framework of adaptable design (Hashemian, 2005). They defined the term of adaptability in adaptable design and then categorized various types of adaptabilities from different views, such as design adaptability and product adaptability, specific adaptability and general adaptability, etc. They also discussed the benefits of adaptable design from perspectives of users, producers and environment. In this framework, a method has been developed for assessing the adaptability of a design based on the amount of “saving” which is achieved via adaptation. However this measurement could not measure the adaptability of a design based on its architectures.
They also provided a brief methodology for adaptable design in which specific adaptability is designed based on predicted information and then general adaptability is achieved by some guidelines to increase the adaptability of the design to unforeseen changes.

Based on the previous framework in adaptable design, some progresses have been made towards the development of adaptable design in depth. Xu et al. presented a framework of design method and realization for adaptable product design and manufacturing (Xu, 2006). For the quantification of adaptability, Fletcher et al. proposed methods for measuring adaptability to represent the initial steps in the process of developing the design tools (Fletcher, 2006). In additional, Shao et al. extended the adaptable design into product family-based adaptable design (PFBAD) (Shao, 2006). Based on the market segment theory, a novel metric for the adaptability of PFBAD was proposed. This metric can be further used to optimize the product family and product platform.

2.5 Review of Research on Design Evaluation Methods

Design decisions are made at different design stages from concept design to detailed design (Otto, 2001). Usually a number of design candidates or different design parameters are created first. These candidates and parameters are evaluated based on the pre-defined evaluation criteria such as performance and cost to select the best candidate and parameter values.
Evaluation of design candidates considering different evaluation measures (criteria) is a typical multiple criteria decision-making problem. Since many design candidates could be created with many design criteria, a computer system is usually needed to improve the quality and efficiency for solving multiple criteria decision-making problems.

In the last two decades, many design evaluation methods have been developed to identify the best design candidate. The Pugh selection chart with a minimal evaluation scale and three overall ranking metrics is usually considered effective for candidate selection when only limited information of design candidates is available (Pugh, 1990). Numerical rankings, weighted sums, general statistics method, utility theory (Raiffa, 1993), and fuzzy sets (Antonsson, 1995) have also been employed for solving multiple criteria decision-making problems. Recently the grey relational analysis method has also been used for evaluating design candidates (Sih, 1997). The grey relational analysis method is used to evaluate design candidates quantitatively. The grey relational analysis has been demonstrated as a simple and effective method for modeling the relationships among different evaluation criteria (e.g., performance and costs) in solving multiple criteria decision-making problems (Chang, 1996; Wu, 2003; Zhang, 2005; Tosun, 2006). This section provides a review of some design evaluation methods.

2.5.1 Traditional Design Evaluation Methods

Pugh selection chart method, as one of the basic evaluation methods, is the most effective method for concept selection when limited information of design is available. With Pugh selection charts, design candidates and criteria are established and displayed on charts.
The design candidates are displayed at the top of the matrix as columns, and the criteria are listed in rows. The next step is to establish the simple evaluation scales of “better”, “worse” or “the same”, and select one candidate that ranks as standard on every criterion and is called as the datum. Every other candidate is compared with this datum with ranking and assessment. With all the candidates rated on every criterion, the ratings are combined into overall scores that can be used to sort the design candidates from the best to the worst. The design candidates with high ranks should be considered (Pugh, 1990).

The basic Pugh section charts use very simple scales: “better”, “worse” and “the same”. The design candidates are simply sorted from the worst to the best. In some case, the design team wants the order reflecting not only whether one alternative is better or worse than another but also how much it is better or worse. To state how much better one design candidate is compared with others, the base point candidate, from which all others are referenced relatively, and an interval scale must be constructed. Krantz et al. developed a basic method called lottery method for constructing interval scales (Krantz, 1971). A numerical concept selection chart can be used to conduct design evaluations by comparative orders. With a numerical concept selection chart, the same as the Pugh selection chart, the design candidates are listed in the columns, and the criteria are listed in the rows. The ratings of each design candidate on different criteria are assigned from a set of integer scales. After the rating process, the sum of rankings for different criteria of each design candidate is achieved. The design candidate with the highest sum is selected as the best candidate.
Using these methods, all the ratings can be simply achieved by a single engineer or by a
group of engineers based on available information and experience of the engineers. For
example, in design concept selection, most traditional evaluation methods are based on
various characteristics of design concepts as evaluation measures. Nevertheless, whether
the measures are quantitative or qualitative, the method uses a rating scale for each
characteristic by experience. However a survey on experience based evaluation methods
shows that they are all less objective and lack accurate data processing (Willis, 1990).

2.5.2 Grey Relational Analysis Approach

Grey theory, established by Deng in 1982, can deal with making decisions characterized
by incomplete information using grey relational analysis (Deng, 1982; Deng, 1989). The
major advantage of grey theory is that it can handle both incomplete information and
unclear problems precisely. In a complex system, when the relationship among various
factors is unclear, such system is called a “grey” system implying poor and incomplete
available information. In this case, the analysis by classical statistical methods may not
be acceptable or reliable without large data sets to satisfy certain mathematical
requirements.

The grey relational analysis is a method in the grey theory to compare evaluation
measures quantitatively. This approach is based on the level of similarity and variability
among all factors to establish their relations. This analytical model magnifies and
clarifies the grey relation among all factors. It also provides data to support quantification
and comparison analysis (Sih, 1997). In other words, the grey relational analysis is a
method to analyze the relational grades among these measures. The grey relational analysis approach requires less data and fewer requirements on data distributions, and can analyze many measures to overcome the disadvantages of traditional statistical analysis methods. In design evaluation, this method can be used to establish the relations among different evaluation measures by comparing the evaluation measures of a particular design candidate with the best evaluation measure considering all design candidates. This method can help the engineers select the best design candidate while significantly reducing rating disputes.

Some researchers made further improvement by combining grey relational analysis and fuzzy methods to develop new evaluation methods. Chang introduced the fuzzy grey relational analysis with new definition of grey relation coefficient and new process to calculate the final grade of alternatives through the fuzzy logic system to develop the evaluation index for ranking priorities (Chang, 1999). Zhang et al. proposed a method of grey relational analysis as a means to reflect uncertainty in multiple criteria models with interval fuzzy input parameters (Zhang, 2005).

Grey relational analysis has been demonstrated as a simple and effective approach for analyzing relationships among different decision parameters (e.g., performance and costs) in multiple criteria decision-making problems. Grey relational analysis in grey theory has also been considerably applied to project selection, performance evaluation, and factor effect evaluation. For example, Tosun used this method to determine the optimal drilling parameters for the multi-performance characteristics (surface roughness and burr height) in the drilling process (Tosun, 2004). Lin and Cheng utilized the grey relational analysis
approach in selecting the most proper location to develop ecotourism by analyzing and evaluating on the aspect of local industries, transportations, agriculture, society, etc (Lin, 2005).

2.6 Summary

In this chapter, Section 2.2 reviewed the axiomatic design theory which is used for establishing the functional structure in adaptable design. Section 2.3 reviewed the research relevant to product configuration design, such as product architecture, modular design, and platform design. Research in this category belongs to the category of design methods for specific adaptability which will be discussed in Chapter 4. Section 2.4 introduced the previous research on adaptable design and the recently progress on design method and quantification of adaptability. Section 2.5 summarized the design evaluation methods that have been achieved in the last two decades to identify the best design candidate.
CHAPTER 3: PRODUCT ADAPTABILITY IN ADAPTABLE DESIGN

3.1 Introduction

In adaptable design, the adaptabilities are classified into design adaptability and product adaptability. Design adaptability is the ability of the existing design to be adapted to create a new design which can serve in a new operational mode. Product adaptability refers to the ability of the physical product to be adapted to various usages or capabilities.

Manufacturers can benefit from adaptable design through the reuse of existing designs to shorten lead times, reduce manufacturing cost and time, reduce the cost of post-sale services, and improve marketing advantage. Users can benefit from adaptable product by: replacing several products with one, easy upgrading to extend service time, and good customization capability.

This thesis mainly focuses on the issues considering product adaptability. Section 3.2 gives definition of the product adaptability and discusses both of specific product adaptability and general product adaptability. The specific product adaptability is composed of extendibility of functions, upgradeability of modules, and customizability of components. Section 3.3 discusses how the product adaptability is implemented in the adaptive design process. The measures of specific product adaptabilities are formulated in details in Section 3.4. Section 3.5 summarizes this chapter.
3.2 Product Adaptability

Product adaptability refers to the ability of a product to be adapted to various usages or capabilities. The adaptation task is usually carried out by users when they want to modify the product to achieve various functions or to enhance its performance (Gu, 2004). Generally users adapt products that have already been created or purchased. Therefore the product adaptability can be considered as a property of the adaptable product. For example, the 2003 Ford Freestyle FX concept car adds a new feature to convert a SUV into a pickup truck, as well as to convert it back. This vehicle is equipped with an electric-powered track for moving the rear trunk module forward and backward. This structure allows for future additions of passenger seats, provides extra space for possible future use of big-size cargo shipment, and the electric-powered track greatly facilitates the adaptation task for users. During the use of this vehicle, the adaptations may happen as the user's needs or conditions change. The structure provides the product adaptability for users to simply carry out the adaptation and to obtain the extended product utility such as shipping big-size cargo function which cannot be provided by a normal SUV in a cost effective manner. Figure 3.1 shows the 2003 Ford Freestyle FX concept car that provides two configurations of SUV and pickup to extend its product utility.

Product adaptabilities can be classified into specific product adaptabilities and general product adaptabilities depending on whether planned information for specific adaptations is available (Gu, 2004). When particular adaptabilities and their possibilities are predicted, the product can be designed to accommodate the specific product adaptabilities. For
achieving some unpredictable requirements and changes, the product can be designed to have some general product adaptabilities by its product architecture and interfaces.

3.2.1 Specific Product Adaptability

In adaptable design, the product is designed to extend for better and/or extra functions. To design the product which has different extra functions, the designers must have some ideas about fundamental functions and adaptable functions at the concept design stage, and then design the product based on these ideas. For example, a computer with an AGP (Accelerated Graphics Port) slot is a typical adaptable design, and this type of computer provides the specific product adaptability. When a computer is sold without the AGP video card, the functions of the computer are the fundamental functions, while the function of the AGP video card is the adaptable function. When a computer with an AGP video card is sold, the function of the AGP video card is also a fundamental function. In this case, the designer can decide whether to add the AGP slot on the motherboard based on the knowledge and needs whether the AGP video card will be used. In generally, specific product adaptability refers to the ability of a product to be adapted to various
usages or capabilities which can be predicted and considered in product design by the designers in advance.

Specific product adaptabilities include extendibility of functions, upgradeability of modules, and customizability of components.

*Extendibility of Functions*

Extendibility of functions is achieved by designing a product with potential functions. Extendibility allows the user to adapt the product from one function to another function with the minimum effort. Extendibility of functions can be obtained by the existing parts designed with versatile functions, or by adding/replacing parts and assemblies of the existing products. For instance, Swiss army knife, shown in Figure 3.2 (a), is a modular platform based design to provide good extendibility of functions. This tool provides more than ten different functions by its knives, scissors, screwdriver, hook and so on without adding any other parts. All of these functions are provided by the existing versatile-designed parts, although some functions are not actually required by the user. On the other hand, the Black and Decker cordless drill, shown in Figure 3.2 (b), achieves its extendibility of functions by replacing its bits. By using the drilling bit, this device can drill holes on the board. This device can also be used to tighten screws by replacing the drilling bit with the screwdriver bit. In the process to design for extendibility of functions, when the forecasted information on product functions is available and these adaptable functions are considered in the design, the designed product then provides both the required fundamental functions and optional adaptable functions.
Upgradeability of Modules

With the advances of technologies and changes of user requirements, the existing products may need to be upgraded to accommodate new technologies or requirement changes. Upgradeability is another kind of product adaptability in which adaptation of existing products to achieve better performance or advanced technologies to meet new needs. For example, the personal computers designed in recent years can be upgraded by the user through changing the components. For example, the motherboard is designed with standard interfaces for the same family of CPUs, RAM memory chips and video cards. Users can get better performance through upgrading the computers with CPUs of higher clock frequency, RAM memories with larger sizes, and 3D video cards with better computation efficiency.

In the process of design for upgradeability, when the components with limited life spans are selected first, the product is designed to accommodate the future upgrading by...
modeling these components as separated modules and associate these modules with standard interfaces with the product architecture.

*Customizability of Components*

Customizability of components is the ease of product adaptation based on requirements and preferences of individual customers. The product design with customizability can be easily reconfigured to different product configurations by combining standard components and modules based on the customer requirements.

In the process of design for customizability, the product should be modeled at two different levels: generic product family and special customized products. Variations of product configurations are modeled in product family. Customized products are identified from the generic product family based on the requirements of customers.

Figure 3.3 gives a summary of the three types of the specific product adaptabilities. It can

![Figure 3.3: Summary of specific product adaptability](image-url)
be seen that specific product adaptabilities can be implemented by adding, replacing, configuring predefined parts through future adaptations by users.

3.2.2 General Product Adaptability

In reality, unanticipated requirements and conditions may arise for an existing product. Although the product is not designed for the unanticipated adaptation, it is still possible to design a product without specific targeted adaptabilities. Such product adaptability without specific purposes is called “general product adaptability”.

To achieve such general product adaptability, this research introduces a new product architecture called “segregated architecture” which is based on the localization of modifications. This architecture of adaptable product is designed to prevent the changes in one place from propagating into the rest of the product (Gu, 2004). The segregated architecture is normally composed by the self-contained and relatively independent assemblies or modules that can be detached, modified, relocated and replaced easily. To make the product more adaptable, the interfaces among assemblies and modules are also designed to ensure the product adaptability.

The LEGO toy system is a typical product with general product adaptability. The LEGO system is an open-ended block building system. Based on the stud-and-tube coupling system that is used to connect LEGO bricks, the LEGO system works on the principle of stacking elements together to build models (LEGO, 2006). The stud-and-tube coupling system is the name of the general interface designed in LEGO. When a user presses two bricks together, the studs and tubes are the primary contact features, and the friction
between these two types of features make the bricks to stick together. LEGO system has more than 2500 different LEGO elements with the same stud-and-tube coupling interface. By using the elements, users can create various configurations. In this case, the LEGO system can successfully build up thousands of models by limited elements, because the design of this toy system has general product adaptability based on its segregated architecture and general interface design. Figure 3.4 shows two different vehicle models built by many LEGO bricks.

3.3 Implementation of Product Adaptability

In adaptable design, designs about how to achieve specific product adaptability and general product adaptability are closely related to designs of base platforms, add-on modules, variant modules, and adaptable interfaces. The product with base platforms, add-on modules, module variants, and adaptable interfaces can provide the ability to adapt the existing product to the changing design requirements for more functions, product customization, upgrading, easy maintenance, parts reuse and so on.
3.3.1 Base Platforms

Base platform of an adaptable product is modeled by a set of common components and modules that are shared by a set of configurations to achieve multiple functions. Base platform usually has longer life span compared with other components and modules of this product, good manufacturing quality, and is considered important for this adaptable product. Product adaptability is initiated by adding, substituting, and/or removing one or more add-on functional modules from the base platform.

As an example, by adding a PCI video capture card on the motherboard, a computer can perform an extra function to convert analog video signals into digital video signals. In addition, the RAM chips on the motherboard can also be replaced to improve the memory size. In this case, motherboard in the computer system is a base platform. The PCI video capture card and the RAM chips are add-on modules.

3.3.2 Add-on Modules

Add-on modules are important for providing the required functions and other life-cycle objectives of products. The modules can be changed according to changes of requirements. These changes would not result in significant impact on the other parts of the product, since add-on modules are independent and self-contained.

Add-on modules can be used to achieve extendibility of functions by changing add-on modules with different functions to obtain multiple functions in a single adaptable product. They can also be used to achieve upgradeability by replacing older modules with new ones to enhance performance and improve service time.
3.3.3 Module Variants

Variants of add-on modules are designed to achieve customizability. The customer’s requirements can be accommodated with variants of add-on modules.

For example, the cell phone manufacturer Nokia always designs its products with changeable covers called Nokia Xpress-on Covers. The covers come in range of designs and colors, so customers can choose a perfect fit for their personal style. The Nokia Xpress-on Covers as module variants provide the customers with various choices in styles and colors. Figure 3.5 shows a Nokia cell phone model with various changeable covers.

![Nokia cell phone with various changeable covers](courtesy of Nokia)
3.3.4 Adaptable Interface

In adaptable products, the physical connections among modules are specially designed so that the functional interactions among the modules permit easy assembly and disassembly. The adaptable interface is a special interface between product base platform and an add-on module or among variants of add-on modules. Adaptable interfaces should satisfy the following requirements: transfer of functions, convenience to use, high reliability, low cost, maximum generality, and self-alignment.

According to the modular architectures developed by Ulrich (Ulrich, 1993), the adaptable interfaces can be classified into three categories: slots, buses and sectionals. The differences among these interfaces are summarized as follows according to the component interactions.

Slot Interfaces

Each of the interfaces between modules in a slot architecture is of a different type from the others, so that the various modules in the product cannot be interchanged. For example, the memory card in digital camera is a module in a slot architecture. The memory card implements only one function and is independent. Its interface is different from any of the other components in the camera (e.g., memory card and battery have different types of interfaces in the camera).

Bus Interfaces

A bus is a standard interface that accepts any different modules with the same type of interface. In the bus architecture, the add-on modules also have a standard interface that
attaches to the bus interface of the base platform. A PCI expansion card for personal computer is a typical example of a module in bus architecture.

Sectional Interfaces

The interfaces among modules are of the same type and there is no single element in the product to which all the other modules are attached. The module with sectional interface is built up by connecting the modules to each other via identical interfaces. Each module may have more than one sectional interface. The studs and tubes in each LEGO brick are sectional interfaces.

Figure 3.6 illustrates three products modeled by simple geometric shapes. The relationships between parts in each product are represented by the connecting lines between these geometric shapes.

![Figure 3.6: Three products modeled by simple geometric shapes](image)

From Figure 3.6, three parts are identically shared by three products. Therefore, the group of three parts which are shared by those products can be considered as a base platform. The other three different parts can be considered as three add-on modules. By considering the connections into the adaptable interfaces between the base platform and the three add-on modules, the new adaptable product can be designed with these interfaces.
Figure 3.7 shows the schematic representation of the adaptable product with slot based interfaces. The arrows with different patterns indicate that each of the interfaces between three add-on modules and the base platform is of a different type. In this case, the variant modules for function 3 are designed to achieve customization and upgrading. Each add-on module can be replaced by another add-on module.

![Figure 3.7: The schematic representation of the adaptable product with slot based interfaces](image)

Figure 3.8 shows the schematic representation of the adaptable product with bus based interfaces. The arrows indicate that each add-on module has a standard interface that is attached to the bus interface of the base platform.

Figure 3.9 shows the schematic representation of the adaptable product with sectional based interfaces. There is no single element to which all the other modules are attached. Each add-on module and the base platform are connected with the same interface.
By designing any types of the above interfaces between the base platform and the three add-on modules, the new adaptable product can be created to accommodate customization and upgrading, as well as to achieve new functions by designing new add-on modules without changing the rest of the whole product.

Figure 3.8: The schematic representation of the adaptable product with bus based interfaces

Figure 3.9: The schematic representation of the adaptable product with sectional based interfaces
3.4 Measures for Evaluating Specific Product Adaptability

This section discusses the measures to evaluate specific product adaptability. These measures are developed based on comparing the effort of an adaptation task with the effort of producing a new product. Therefore, these measures can be achieved when the adaptation task is known. Since the general product adaptability is based on the unanticipated adaptation, the measures are only used for evaluating specific product adaptability.

3.4.1 Extendibility, Upgradeability, and Customizability

In this research, three evaluation measures, extendibility of functions, upgradeability of modules, and customizability of components, are introduced for evaluating specific product adaptability.

*Extendibility of Functions*

Extendibility of functions is obtained by a product which is designed with multiple functions. In this research, functions of an adaptable design are classified into two categories: fundamental functions and adaptable (optional) functions. For example, a computer with an AGP slot is a typical adaptable design. When a computer is sold without the AGP graphics card, the functions of the computer are the fundamental functions, while the function of the AGP graphics card is the adaptable function. When a computer with an AGP graphics card is sold, the function of the AGP graphics card is also a fundamental function.
Suppose the probability to adapt the current product with an adaptable function $T_{p_i}$ (i.e., the i-th target adaptation) in the future is defined as $Pr(T_{p_i})$, the effort to adapt the current product to the adaptable function $T_{p_i}$ is described by $Inf(S_1 \rightarrow AM_2)$, and, the effort to create a completely new product with the same function is described by $Inf(ZERO \rightarrow IS_2)$. The extendibility factor, $EF(T_{p_i})$, is then defined by:

$$EF(T_{p_i}) = 1 - \frac{Inf(S_1 \rightarrow AM_2)}{Inf(ZERO \rightarrow IS_2)}, \quad 0 \leq EF(T_{p_i}) \leq 1$$  \hspace{1cm} (3.1)

When all $n$ possible adaptable functions are considered, the extendibility of the existing product is defined by:

$$E(P) = \sum_{i=1}^{n} [Pr(T_{p_i})EF(T_{p_i})]$$  \hspace{1cm} (3.2)

In this method, the costs are usually selected to describe the efforts for adapting an existing product or for creating a new product. In Eq. (3.1), the efforts to adapt an existing product or to create a new product are defined by:

- $S_1$: the current state of the existing product,
- $AM_2$: the modified state with the additional adaptable function,
- ZERO: the state to design a new product from scratch, and
- $IS_2$: the state with only the required adaptable function.

From Eq. (3.1), when the effort for adapting an existing product is greater than the effort for creating a new product, the extendibility factor is calculated as 0. In this case, no adaptation is required. When the effort for adapting an existing product is smaller than the effort for creating a new product, the extendibility factor is calculated as a value
between 0 and 1. In this case, adaptation of the existing product should be considered.
When no extra effort is required to achieve the adaptable function from the existing product, the extendibility factor of this product is 1.

For example, FM radio and flashlight are useful tools for camping. The FM radio can be used to learn the up-to-the-minute weather updates. The flashlight is used in the dark areas. Usually the FM radio and flashlight are sold separately. Since both of them use similar DC power systems, considerable redundancy functions can be found in these products. In the design of a new product by considering product adaptability, the FM radio can be designed as a fundamental function, and the flashlight can be designed as an adaptable function. The function of flashlight can be achieved by an add-on module of LED bulb. When the LED-bulb module is attached to the FM radio base with an interface, the FM radio will provide the power supply to the LED bulb.

In this case, S1 is the state that the product has only the FM radio function without considering the flashlight function. AS2 is the state that the product provides both the FM radio function and the flashlight function. IS2 is the state with only the flashlight function. The $f(sI\rightarrow AS2)$ is then the cost to change the existing design of FM radio to the new design with both the FM radio function and the flashlight function. The $Inf_{(\text{ZERO} \rightarrow IS2)}$ is the cost of the new flashlight.

Assume the cost to build a new flashlight product is $10, and the cost to add a flashlight function to S1 is $2, the extendibility factor $EF(Tp_1)$ can be calculated by:
From the result, the extendibility factor is calculated as a value between 0 and 1. In this case, adaptation of the existing product should be considered, since it is cheaper to adapt the FM radio with the flashlight function than to create a new product of the flashlight.

If the cost to build a new flashlight product is $10, and the cost to add a flashlight function to S1 is $12, the extendibility factor $EF(Tp_1)$ can be calculated by:

$$EF(Tp_1) = 1 - \frac{Inf_{(S1 \rightarrow AS2)}}{Inf_{(ZERO \rightarrow IS2)}} = 1 - \frac{2}{10} = 0.8$$

Since value of $EF(Tp_1)$ is negative, the extendibility factor is calculated as 0. In this case, adaptation of the existing product should not be considered, because it is more expensive to adapt the FM radio with the flashlight function than to create a new product of the flashlight.

If no extra cost is required to add a flashlight function to S1, the extendibility factor $EF(Tp_1)$ of this product is calculated by:

$$EF(Tp_1) = 1 - \frac{Inf_{(S1 \rightarrow AS2)}}{Inf_{(ZERO \rightarrow IS2)}} = 1 - \frac{0}{10} = 1$$

Upgradeability of Modules

When technologies and user requirements are changed, the adaptable product should accommodate these changes through an upgrading process. Upgradeability is another
evaluation measure of product adaptability in which the existing products are adapted based on the new requirements.

Suppose the probability to upgrade the current part with an upgraded part \( U_{Pi} \) (i.e., the \( i \)-th target upgrading) in the future is defined as \( Pr(U_{Pi}) \), the effort to provide the upgrading function in the current part is described by \( Inf_{(P_{i} \rightarrow U_{Pi})} \), and, the effort to create current part without upgrading capability is described by \( Inf_{(P_{i})} \). The upgradeability factor, \( UF(U_{Pi}) \), is then defined by:

\[
UF(U_{Pi}) = 1 - \frac{Inf_{(P_{i} \rightarrow U_{Pi})}}{Inf_{(P_{i})}}, \quad 0 \leq UF(U_{Pi}) \leq 1
\]  

(3.3)

When all \( n \) possible upgrading parts are considered, the upgradeability of the existing product is defined by:

\[
U(P) = \sum_{i=1}^{n} [Pr(U_{Pi})UF(U_{Pi})]
\]  

(3.4)

In this method, the costs are usually selected to describe the efforts for providing the upgrading function and for creating the part without upgrading function. Generally, the cost for providing upgrading function is calculated by the cost of the interface which allows for the upgrading of the new part. In Eq. (3.3), the effort for providing upgrading function is defined by:

\[
P_{i}: \quad \text{the physical state of the part without upgrading function}
\]

\[
UP_{i}: \quad \text{the physical state of the part with upgrading function}
\]
From Eq. (3.3), when the effort for making available to upgrade an existing part is greater than the effort for creating this part, the upgradeability factor is calculated as 0. In this case, no upgrade is advised. When the effort for a making available to upgrade an existing part is smaller than the effort for creating this part, the upgradeability factor is calculated as a value between 0 and 1. In this case, upgrade of the existing part should be considered. When no extra effort is required to achieve the upgrade from the existing part, the upgradeability factor of this part is 1.

Continue with our previous example, the rechargeable battery of the FM radio can be considered as an upgradeable part. It can be upgraded by new types of battery with larger capacity in the future. To provide this upgrading function in the FM radio, a user-friendly interface for upgradeable battery needs to be designed and built in advance. On the other hand, if the battery is considered as a non-upgradeable part, the interface of non-upgradeable battery will be different from the interface of upgradeable battery.

In this case, P1 is the state of the battery without an interface for upgrading. UP1 is the state of the battery with an interface for upgrading. The $Inf_{P1 \rightarrow UP1}$ is then the cost to provide the interface for upgrading function of the battery. The $Inf_{P1}$ is the cost to create the battery without upgrading capability.

Assume the cost to build a rechargeable battery without upgrading capability is $5, and the cost to provide a user-friendly interface for upgrading function of the battery is $1, the upgradeability factor $UF(Up_1)$ can be calculated by:
From the result, the upgradeability factor is calculated as a value between 0 and 1. In this case, upgrade of the battery should be considered.

If the cost to build a rechargeable battery without upgrading capability is $5, and the cost to provide a user-friendly interface for upgrading function of the battery is $6. The upgradeability factor $UF(Up_1)$ can be calculated by:

$$UF(Up_1) = 1 - \frac{Inf_{(P_1 \rightarrow UPl)}}{Inf_{(P_1)}} = 1 - \frac{6}{5} = -0.2$$

From the result, the upgradeability factor is calculated as 0. In this case, upgrade of the battery should not be considered, since the cost for upgrading the battery is too high.

If no extra cost is required to provide the user-friendly interface for upgrading function, the upgradeability factor of the battery is calculated by:

$$UF(Up_1) = 1 - \frac{Inf_{(P_1 \rightarrow UPl)}}{Inf_{(P_1)}} = 1 - \frac{0}{5} = 1$$

**Customizability of Components**

Customization is the adaptation of a product based on requirements and preferences of customers. The product with ability of customization can be easily developed into many models which provide various combinations of features in response to various customer requirements. In this work, the customization mainly focuses on part customization.
Same as the upgradeability, suppose the probability to customize the current part with another part with same function $Cp_i$ (i.e., the $i$-th target customization) in the future is defined as $Pr(Cp_i)$, the effort to make available to customize the current part to the another part $Cp_i$ is described by $Inf_{(P1\rightarrow CPI)}$, and, the effort to create current part without the customizability is described by $Inf_{(P1)}$. The customizability factor, $CF(Cp_i)$, is then defined by:

$$CF(Cp_i) = 1 - \frac{Inf_{(P1\rightarrow CPI)}}{Inf_{(P1)}}, \quad 0 \leq CF(Cp_i) \leq 1 \quad (3.5)$$

When all $n$ possible customization parts are considered, the customizability of the existing product is defined by:

$$C(P) = \sum_{i=1}^{n} [Pr(Cp_i)CF(Cp_i)] \quad (3.6)$$

When the selected customization part is also an upgradeable part and they can share the same interface, there is no extra effort required to achieve the customization from the existing part.

### 3.4.2 Specific Product Adaptability Index

The specific product adaptability index is based on three main measures: (1) extendibility of functions, (2) upgradeability of modules, and (3) customizability of components. Each of these measures results in a percentage of specific product adaptability, which can then be combined to determine an overall measurement of specific product adaptability for a design candidate of the product by using appropriate weights for each item.
To use the above three different evaluation measures, these measures should be converted into dimensionless evaluation measures in advance. The normalized measure for extendibility of functions is calculated by

\[ NE(P)_i = \frac{E(P)_i}{E(P)_{\text{max}}} \]  

(3.7)

where:

- \( E(P)_i \) - extendibility of functions of the i-th design candidate
- \( E(P)_{\text{max}} \) = the maximum value of extendibility of functions considering all the compared design candidates

Similarly, the upgradeability of modules and customizability of components can be calculated in the same manner:

\[ NU(P)_i = \frac{U(P)_i}{U(P)_{\text{max}}} \]  

(3.8)

\[ NC(P)_i = \frac{C(P)_i}{C(P)_{\text{max}}} \]  

(3.9)

These three values can then be combined into an overall specific product adaptability index in several different manners. The most useful one is the weighted-sum formulation. The specific product adaptability index of the i-th design candidate is calculated by:

\[ A(P)_i = \frac{I_E \times NE(P)_i + I_U \times NU(P)_i + I_C \times NC(P)_i}{I_E + I_U + I_C} \]  

(3.10)

where:

- \( I_E, I_U \) and \( I_C \) are weighting factors satisfying \( \sum I = 1 \)
In this research, the weighting factor of each evaluation measure is defined equally as 33.3%, because extendibility of functions, upgradeability of modules, and customizability of components are considered the same important level for specific product adaptability.

The result of specific product adaptability index $A(P)$ of each design candidate ranges from 0 to 1. When $A(P)=0$, there is no specific product adaptability; When $A(P)=1$, the design candidate has ideal specific product adaptability.

3.5 Summary

This chapter discussed the product adaptability in adaptable design. Section 3.1 overviewed the definition of adaptability. Section 3.2 explained two types of product adaptability: specific adaptability and general adaptability. Section 3.3 presented the methods on how to implement product adaptability by organizing components of products as base platforms, add-on modules, module variants, and adaptable interfaces. Section 3.4 introduced three measures for evaluating specific product adaptability.

The next chapter will present the design methodology and design process in adaptable design to show how the product adaptability can be achieved.
CHAPTER 4: DESIGN PROCESS FOR PRODUCT ADAPTABILITY

4.1 Introduction

Adaptable design was introduced based on the techniques of platform design and modular design (Gu, 2004). During the design process, adaptable design also emphasizes the adaptable interface design to consider the product adaptability and design adaptability. Adaptable product, as the result of adaptable design, has many advantages, including extendibility of functions, upgradeability and customizability of modules, etc. To achieve these benefits, the product must be designed to provide the product adaptability.

This chapter presents the method of design process considering product adaptability in details. This design process for product adaptability is composed of 5 phases with 6 major steps. Section 4.2 gives an overview of the methodology with the core tasks in the 6 major steps. Section 4.3 presents the design process with 5 phases: function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation and detail design. Section 4.4 summarizes this chapter.

4.2 Overview of Methodology

The design methodology for product adaptability is used for creating the product which can be adapted by the user and the manufacturer to extend its utility. This approach can also be used for reducing the environmental impacts of the products by improving the product adaptability through the reuse of components and add-on modules, upgrade of
products, quick replacement of components for easy maintenance, and recycling of components and materials.

The design process for product adaptability is composed of 5 phases: function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation and detail design with 6 major steps of the design process, as shown in Figure 4.1.

Figure 4.1: The schematic of design process for product adaptability

The core tasks in these major steps are summarized as follows.
1. **Product Planning:**

Product planning starts with developing the mission statement for the product. This step includes defining the adaptable design mission statement, identifying customer needs, determining the primary functional requirements (FRs) and the optional FRs, and establishing the tree for modeling the FRs and the tree of design parameters (DPs) to satisfy the FRs.

2. **Studying Modularity:**

In this step, the functional elements are grouped into modules. The components with dependent relations of design functions are grouped into modules. The study provides the fundamental structure of the product modularity.

3. **Establishing Product Architecture:**

Develop the product architecture based on clusters of modules and product model to describe the flows of material, energy and signals through the system. Create the rough geometric layout. This is the most creative part in adaptable design. And then identify the interactions among modules.

4. **Adaptable Interface Design:**

Develop the interface and connectors so that functions can be transferred between the platform and the modules, and among modules.

5. **Concept Design Evaluation:**

Identify the different fundamental functions and adaptable functions of every design solution and organize the different configurations into various design candidates. Evaluate each design candidate with four main evaluation measures, including specific
product adaptability of design, part cost, assembly cost, and operation ability of customers. Prioritize the design candidates by using grey relational analysis approach which will be introduced in Chapter 5.

6. **Detail Design:**

Once the product configuration architecture has been identified, the fundamental functions and adaptable functions have been chosen, and the best design candidate has been determined, the product can then be designed in details. The selected design concept based on evaluation will be developed into actual parts and assemblies through geometry modeling using a computer-aided design (CAD) system.

### 4.3 Design Process for Product Adaptability

All the steps in the design process given in Section 4.2 are then grouped into 5 design phases: function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation and detail design. In this section, the guidelines and methods in this design process for product adaptability will be presented in details.

#### 4.3.1 Function Modeling

To achieve a successful function modeling, a good product planning plays an important role. Product planning starts with the mission statement for the product. This step includes defining the adaptable design mission statement, identifying customer needs, determining the primary functional requirements (FRs) and the additional FRs, and decomposing functional requirements and generating design parameters (DPs). Finally
the trees for modeling the functional requirements (FRs) and design parameters (DPs) to satisfy the FRs can be created in this phase.

**Step 1: Defining the Adaptable Design Mission Statement**

At the beginning of the product development, the design team typically prepares a document as mission statement to specify the design information, such as a brief description of the product, objectives, assumptions and constraints, target market, etc. The mission statement shows the directions but does not specify a particular way to proceed. In addition, the mission statement can be used to lead to discussion for gathering the customer needs. The detailed steps of generating mission statement were explained by Ulrich (Ulrich, 2001).

**Step 2: Identifying Customer Needs**

There are several methods available for design team to gather the customer needs. Four methods are commonly used: interviews, questionnaires, focus groups, and observing the product in use (Otto, 2001). After the customer analysis, including grouping the needs and determining need importance factors, has been completed, the result can be summarized as a reference for the design team.

**Step 3: Determining the Fundamental FRs and Adaptable (Optional) FRs**

To determine the fundamental FRs and adaptable (optional) FRs, a group of products that can be developed from a shared platform should be identified first. For example, various electric-motor-driven based small appliances, such as stand mixers, hand mixers,
blenders and meat grinders, are used for processing different types of foods in the kitchen. Since most of them have similar power driven and control sub-systems, these food processing appliances can be developed from a shared platform.

From the identified group of products, the fundamental FRs and adaptable (optional) FRs are defined after the different features and common elements among the products in this group are identified.

**Step 4: Decomposing Functional Requirements**

In the adaptable design method, a functional requirement (FR) is usually decomposed into sub-FRs to divide a system into smaller, coherent, self-contained functional elements. The decomposition is performed only after a solution for the FR is found. The function decomposition method in the axiomatic design approach (Suh, 2001) is employed in this research for developing the design process model.

Axiomatic design methodology provides a top-down decomposition process. The frame constructed in the top level is decomposed into hierarchies. This process is also constrained by relational mapping domain (Suh, 2001).

The axiomatic design includes the following main concepts.

1. Domains, which separate the functional descriptions and physical descriptions of the design.

2. Hierarchies, which categorize the progress of a design in the functional and physical domains from the systemic level to more detailed levels.
(3) Zigzagging, which indicates that the decisions made at one level of the hierarchy affect the problem statement at lower levels of the hierarchy.

(4) Design Axioms, which require that the independence of the functional requirements must be maintained, and the information content (i.e., cost, complexity, etc.) must be minimized, in order to generate a design with good quality.

A design is usually started by defining the objectives and requirements. These objectives and requirements are modeled in functional domain in axiomatic design, while the physical solutions are modeled in the physical domain. In axiomatic design, these two domains are linked by their relations.

The next step is to determine the objectives of the design by defining them in terms of specific FRs. To satisfy these functional requirements, a physical embodiment is developed in terms of DPs. The design process associates the FRs in the functional domain to the DPs in the physical domain through zigzagging mapping.

Design axioms provide principles that aid the creative process by enabling good designs to be identified. In mathematical terms, the design can be represented as follows:

\[
\{FR\} = [A]\{DP\} \tag{4.1}
\]

where:

\(\{FR\} = \) vector of the functional requirements

\([A] = \) design matrix associating the functional domain with the physical domain

\(\{DP\} = \) vector of the design parameters
Each possible solution from the same functional requirements is modeled by one design matrix. As shown in Figure 4.2, a diagonal matrix represents that the design is an uncoupled design. A triangular matrix indicates that the design is a decoupled design. A full matrix means that the design is a coupled design.

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
A_{11} & 0 & 0 \\
0 & A_{22} & 0 \\
0 & 0 & A_{33}
\end{bmatrix}\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\]

Uncoupled

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
A_{11} & 0 & 0 \\
A_{21} & A_{12} & 0 \\
A_{31} & A_{32} & A_{13}
\end{bmatrix}\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\]

Decoupled

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\]

Coupled

**Figure 4.2: The graphical representations and design matrices of the three types of designs**

The uncoupled design and decoupled design satisfy the Axiom 1 in axiomatic design, i.e., the independence of FRs is assured if DPs are arranged in a certain order. Since the components and modules in an adaptable product need to be changed, all these components and modules should be designed as independent as possible to minimize potential propagation of changes. By using the axiomatic design as a guide, the product can be designed to satisfy the Axiom 1. This method can enhance both specific and general product adaptabilities by the independent structure of the product.

After the function modeling, the FRs and DPs trees can be established to help the design engineers achieve the adaptable platform/modular design.
4.3.2 Adaptable Platform/Modular Design

Adaptable platform/modular design is conducted to achieve various objectives such as upgrading, customization, and so on based on the functions of modules. These objectives are related to the primary benefit of adaptable design, that is, extension of product utility. In this phase of design, a design process has been introduced in this work based on the four-step process given by (Ulrich, 1995) for establishing the product architecture.

After the step to create a schematic of the product considering modularity using the trees of functional requirements and design solutions, the created elements are then grouped into modules by some guidelines. The components and modules with shared functions are identified as the core elements. The product architecture and interactions among modules are also created in this phase.

Step 1: Creating a Schematic of the Product

Based on the result of DPs created from the axiomatic design, this step aims at creating a schematic of the product. A schematic is a diagram representing the designer's understanding of the elements and their relations to model a product (Ulrich, 2004). Flows of material, energy and signal are also presented in the schematic.

In the schematic, the functional elements are presented as blocks. The functional elements of the product are formed by the DPs which have not been designed into physical components. For example, “steering system” is a functional element in the product of an electric vehicle, but the specific mechanism for performing steering function has not been decided. The dependency relations among these blocks are
described by arrowed lines. Different types of lines represent different types of dependency relations: material relations, energy relations, and signal relations, as shown in Figure 4.3.

![Figure 4.3: Different types of lines representing different types of dependency relations in schematic of product (Otto, 2001)](image)

The schematic with fully connected blocks reflects a feasible state of the product. However, the full details are not included in this schematic. The schematic is used to identify high-level functional elements. It is not used to generate detailed design solutions. The created schematics are not unique. Each is created depending on the functional elements and their relations. For example, different schematics for a can opener can be created depending on the input power sources: manual or electrical. In this step, alternative schematics should be developed first to identify the best design candidate from the group through evaluation to all the feasible candidates.
Step 2: Clustering the Functional Elements into Modules

After creating one or more schematics of the product, the next step is to group the functional elements into modules for each schematic. Module is defined as a component or group of components that can be removed from the product non-destructively as a unit which provides a unique basic function necessary for the product to operate as desired. Modularity has been defined as the degree to which product architecture is composed of modules with the minimal interactions between modules.

The process for identifying modules is known as the approach of clustering (Ulrich, 2004). Modules are chosen by grouping several functional elements which depend on each other or can be solved together. By simplifying the interactions, each module will be as independent as possible. The independence of module can provide better flexibility and adaptability in the adaptable product. Simple interactions will also reduce the possibility of failure and difficulties of manufacturing at the interfaces of modules.

Some general guidelines for clustering functional elements into modules for adaptable design are summarized as follows. These guidelines can be applied iteratively through the design process.

1. Combine as many functional elements into a module as possible. This provides the opportunity to simplify the complexity of product and reduce the redundant interfaces. For example, from Figure 4.4, the functional elements of time display, time setting and mode selection in the newly designed microwave oven have been clustered into the same module.
2. Based on the predictions of future changes or evolutions for the product, the functional element with possibility of future changes should be separated as an add-on module. The add-on module is designed according to the expected changes, such as upgrading, replacing, etc. These designs can be carried out without considering the functions of the other modules. Add-on modules can also be used to achieve extendibility of functions by changing add-on modules with different functions to obtain multiple functions in a single adaptable product.

3. After identifying the customizable functional elements, the selected function elements should be clustered into customization modules separately. The variants of a customization module can be designed to achieve customizability.

4. Modules for base platform should be chosen based on what will be shared by a set of configurations to achieve multiple functions.
5. Modules should be clustered with flexible interactions. For example, electrical signals are much more flexible than the mechanical forces and motions. As a result, modules with electronic interactions can be easily separated.

Step 3: Creating a Rough Geometric Layout

When modules have been decided, the next step is to create a rough geometric layout of the product. This layout can be presented in 2-D or 3-D models by using drawings and CAD systems. This is the most creative part in adaptable design.

During the process to create the geometric layout, the design team needs to make decisions by considering the interfaces among the modules and the basic geometric relationships among the modules. Because the modules are created in the previous step, in some case some modules are not geometrically feasible and thus some of them have to be re-created.

Some general guidelines are summarized as follows for creating rough geometric layout:

1. The modules which are created in previous step might be recreated when layout is developed to achieve a feasible configuration.

2. Various configurations should be developed first for identifying the best geometric layout from all feasible geometric layouts.

3. Layouts should be created aesthetically and ergonomically, based on the customer needs. The industrial designers need to cooperate with the design team to link the aesthetic design to its engineering functions.
Step 4: Identifying the Interactions

When suitable rough geometric layout has been created, interactions between modules in the layout must be defined. To define the interactions between modules, the material, energy and signal flows must be identified at each module boundary. Cutherell summarized four types of interactions as follows (Cutherell, 1996):

1. Material interactions: solid, liquids, or gases that flow from one module to the next.
2. Energy interactions: energies or forces that must be transmitted or shielded between modules.
3. Information interactions: signals (such as: electrical, tactile, etc.) that much be processed from one module to the next.
4. Spatial interactions: geometrical dimensions, degrees-of-freedom (DOF), tolerances and constraints that must be maintained between modules.

Step 5: Establishing the AND-OR Tree

At the last step in this phase, the conceptual result of each design candidate is modeled by an AND-OR tree based on the structures of product.

When a product structure is decomposed into a number of sub-structures, these sub-structures are associated with an AND relation. When a product structure is satisfied by alternative sub-structures, these sub-structures are associated with an OR relation. The customization modules and upgradeable modules in the AND-OR tree are described by the symbols of C and U. Figure 4.5 shows a generic type of design candidate structure.
4.3.3 Adaptable Interface Design

To modularize mechanical components, the physical interfaces among modules must be specially designed so that the functional interactions among modules and operations of assembly and disassembly can be easily achieved. To design the adaptable interface, the third phase of the design process aims at developing the interface and connectors, so that functions can be transferred between the base platform and the modules, and among modules.

According to the modular architectures developed by Ulrich (1995), the adaptable interfaces can be classified into three categories: slots, buses and sectionals. Usually one product may exhibit many types of interfaces. The designers can choose different types of interfaces in different places of a product. Adaptable interfaces should satisfy the
following requirements: transfer of functions, convenience to use, high reliability, low cost, maximum generality, and self-alignment. These features should be considered in the design process.

1. Transfer of functions: As an interface is primarily a connective structure for both physical connection and function transfer.

2. Convenience to use: The mechanisms of interfaces between base platform and the modules, and among modules need to be designed for easy to use. For example, a design of lock-and-release mechanism which can be operated with a trigger to release is better than the design of bolt connection.

3. High reliability: The interface mechanism must be strong enough to restrict remaining degrees of freedom by the structure design and rigidity of material.

4. Low cost: Because the interface cost will be counted into part cost, the cost of interface should be minimized by selecting the best economic connector design.

5. Maximum generality: To minimize the cost and complexity of the product, the types of interface should be designed with maximum generality.

6. Self-alignment: Mechanisms of the interface should be designed to connect to each other with self-alignment. The features of interface must mate effectively.

To design the adaptable interface with the above key features, the first step is to analyze features of modules, and then to cluster those features into different categories. Based on the information in different categories, the interface can then be designed with a number of key features in the detail design phase.
4.3.4 Concept Design Evaluation

By following the guidelines introduced in previous sections, the design engineers may achieve different design candidates, which all are adaptable and fulfill the design requirements. Therefore evaluation of these design candidates is required.

In this research, a new method to evaluate design candidates in adaptable design is introduced by using the grey relational analysis approach. These design candidates are evaluated by different life-cycle evaluation measures including specific product adaptability, part and assembly costs of manufacturing, operationability of customers, etc. The grey analysis approach is employed in this research to integrate the different evaluation measures for prioritizing different design candidates with different fundamental and adaptable functions.

This method is used to establish the relations among different evaluation measures by comparing the evaluation measures of a particular design candidate with the best evaluation measures considering all design candidates. At the end, the best design candidate can be selected based on the rankings of all the design candidates. More details of the evaluation method will be discussed in the next chapter.

4.3.5 Detail Design

When the best design candidate has been chosen after the evaluation and prioritization, the selected best candidate can then be designed in details. The detail design of the product, including the interface design, requires considerable design effort.
This phase of design process includes industry design, engineering design analysis, dynamic analysis, and so on. Many CAD/CAM/CAE software systems are used for detail design. The result of the detail design is the complete design model with components and assemblies ready for manufacturing. In this thesis, some results of the detail design of case study are presented in Chapter 6.

4.4 Summary

This chapter presented the method and design process of adaptable design on how to achieve the product adaptability. Section 4.2 gave an overview of the design method for product adaptability, which is composed of 5 phases: function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation, and detail design within 6 major steps of design process. Section 4.3 presented the guidelines and methods in this design process for product adaptability.

The next chapter will present the evaluation method for design concept selection in adaptable design by using the grey relational analysis approach. The different design candidates created in adaptable design are evaluated by the different evaluation measures for prioritizing different design candidates with different fundamental and adaptable functions.
CHAPTER 5: EVALUATION OF DESIGN CANDIDATES

5.1 Introduction

Design candidate selection is very important in the product development process. In order to reduce the part cost and assembly cost, and improve product operationability and the product adaptability, it is necessary to select the most appropriate design candidate at a conceptual design stage. In adaptable design, the design candidates generated following the guidelines of adaptable design process can embody the characteristics of segregated architecture. But different design candidates may have different segregated architectures. Due to the different architectures in diverse design candidates, the physical modules that provide distinct functions and the interfaces among different modules are usually different (Ulrich, 2004). Therefore, evaluation of the different design candidates with different architectures is required for selecting the best design candidate.

Design candidate selection through evaluation of these candidates considering different evaluation measures is a typical multiple criteria decision-making problem. The key issue in solving this problem is to convert the different evaluation measures with different units into comparable evaluation indices.

In the last two decades, many concept selection approaches have been achieved to help to choose among design candidates. Although considerable methods, such as concept selection charts, are introduced to help make decision, many designers, students and instructors do not believe in the mechanics of these methods. When using a Pugh selection chart (Pugh, 1990) with a minimal evaluation scale of \{-, S, +\} for evaluating...
concepts, people often feel uncomfortable using the highest scoring result. They often ask what the differences in numbers really mean (Otto, 1995). The methods are, however, usually effective for candidate selection when limited information of design candidates is available. These methods can be used to quickly form group consensus on major issues. On the other hand, numerical rankings, weighted sums, utility theory, and fuzzy sets have also been advocated for solving multiple criteria decision-making problems (Otto, 2001).

By the above methods, many of the decisions are simply made by a single engineer or a small group of engineers, based on accessible information and the experience of the engineers. However, a survey on this experience based evaluation methods shows that they are all less objective and lack accurate data processing (Willis, 1990). For example, in design concept selection, most commonly used evaluation methods are based on various characteristics of design concept as evaluation measures. Nevertheless, whether the measures are quantitative or qualitative, the method uses a rating scale for each characteristic. The numeric score for each measure will be weighted by a factor, and then sum of the weighted scores is achieved. As a result, the design with the highest score is considered as the best design concept.

Since decision to select the design candidate is conducted at early conceptual design stage, the information of design candidates is usually limited, incomplete and uncertain. The relationship among various evaluation measures is also unclear. In this case, the analysis by classical statistical procedures for multiple criteria decision-making may not be acceptable or reliable without large data sets that satisfy certain mathematical criteria.
The grey relational analysis is known as a method in the grey theory (Sih, 1997) that compares evaluation measures quantitatively whether the measures are quantitative or qualitative. Since grey relational analysis makes use of relatively small data sets and does not demand strict compliance to certain statistical laws, it can be applied when sample size is small and sample distribution is unknown. The grey relational analysis has been demonstrated as a simple and effective approach for analyzing relationships among different decision parameters (e.g., performance and costs) in multiple criteria decision-making problems (Chang, 1996; Wu, 2003; Zhang, 2005; Tosun, 2006).

Based upon the concepts of grey relational analysis, this thesis employs the grey relational analysis approach to integrate the different evaluation measures for prioritizing different design candidates with different fundamental and adaptable functions.

This chapter presents the evaluation method for design concept selection in adaptable design. Section 5.2 discusses the evaluation measures which are used in the introduced evaluation method. Section 5.3 presents the evaluation method and detailed steps for design concept selection. Section 5.4 provides a brief summary of this chapter.

5.2 Evaluation Measures

From the discussion in Chapter 3, specific product adaptability is an evaluation measure from the design perspective that considers functions, upgrade of functions and customizations. Since different evaluation measures from different product life-cycle
aspects – including manufacturing costs, ease of operation, etc. – also influence the competitiveness of the product, evaluation of the adaptable designs considering all relevant life-cycle aspects has to be carried out.

Evaluation of a design considering different evaluation aspects is a typical multiple criteria decision-making problem. Usually these different evaluation measures are modeled with different units representing quantitative and qualitative information of products.

In the evaluation model of this research, four evaluation measures – specific product adaptability, total part cost, total assembly cost, and operationability of customers – are selected for evaluating design candidates.

*Specific Product Adaptability*

The fundamental functions and adaptable functions of a product are identified by the forecast information of particular adaptabilities and possibilities at the marketing stage, and then the product is designed to accommodate the product adaptabilities. Such product adaptability is called “specific product adaptability”. The measures for evaluating specific product adaptability are formulated in Chapter 3.

*Total Part Cost and Total Assembly Cost*

Total part cost for each product candidate is the sum of the costs of all parts. Assembly cost is the cost for all assembly activities. Different product architectures usually require different assembly costs. Since the product architecture and interface of each product
candidate are established in the previous design phases, the part cost and assembly cost can be represented quantitatively.

*Operationability*

The operationability of a product is evaluated based on convenience of interface, degree of difficulty to adapt to different functions, and the feelings of customers. Because the operationability is evaluated in terms of good, fair, and poor, this evaluation measure is qualitative in nature. Operationabilities are rated on scales between 0 and 5, representing totally unsatisfactory and totally satisfactory, respectively.

These 4 evaluation measures are summarized in Table 5.1.

<table>
<thead>
<tr>
<th>Evaluation Measure</th>
<th>Life-cycle Aspect</th>
<th>Type of Measure</th>
<th>Calculation</th>
<th>Operationability</th>
</tr>
</thead>
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<td>Adaptability</td>
<td>Design</td>
<td>Quantitative</td>
<td>Eq. (3.10)</td>
<td>Operation</td>
</tr>
<tr>
<td>Part Cost</td>
<td>Manufacturing</td>
<td>Quantitative</td>
<td>Sum of Costs of All Parts</td>
<td>Qualitative</td>
</tr>
<tr>
<td>Assembly Cost</td>
<td>Manufacturing</td>
<td>Quantitative</td>
<td>Sum of Costs for All Assembly Activities</td>
<td></td>
</tr>
<tr>
<td>Operationability</td>
<td></td>
<td></td>
<td>Rating on Scale of 0-5</td>
<td></td>
</tr>
</tbody>
</table>

5.3 Evaluation Steps by Using Grey Relational Analysis (GRA) Approach

Since different evaluation measures of adaptable designs are usually modeled with different units, these measures need to be converted into comparable measures for evaluating different design candidates. In this research, the grey relational analysis method has been employed for integrating the different design evaluation measures into
the same environment.

The grey relational analysis is a method in the grey theory to compare evaluation measures quantitatively. This method is used to establish the relations among different evaluation measures by comparing the evaluation measures of a particular design candidate with the best evaluation measures considering all design candidates. The grey relational analysis approach requires less data and fewer requirements on data distributions, and can analyze many measures to overcome the disadvantages of traditional statistical analysis methods.

Evaluation of adaptable designs by using the grey relational analysis approach is conducted in the following 6 steps.

1. Establish comparative series and standard series.

The comparative series is an information series with \( m \) adaptable design candidates and \( n \) evaluation measures described by:

\[
A_i = (x_{i1}, x_{i2}, \ldots, x_{ij}, \ldots, x_{in}), \quad i = 1, 2, 3, \ldots, m
\]

where \( x_{in} \) denotes the \( n \)-th evaluation measures of the \( i \)-th candidate.

The \( m \) adaptable designs and the \( n \) evaluation measures of these adaptable designs form an \( m \) by \( n \) decision matrix, \( D \).

The standard series is a target series modeled by:

\[
A_0 = (x_{01}, x_{02}, \ldots, x_{0j}, \ldots, x_{0n})
\]

The standard series is composed of the best values for each of all the evaluation measures.
2. Generate the normalized decision matrix $K$ (dimensionless).

To compare the different evaluation measures, these measures should be converted into dimensionless evaluation measures through the following 3 steps.

(a) If the evaluation measure is of the larger-the-better type (e.g., the adaptability), the normalized measure is calculated by:

$$x^*_y = \frac{x_y - \min_{i} x_{ij}}{\max_{i} x_{ij} - \min_{i} x_{ij}}$$  \hspace{1cm} (5.3)

(b) If the evaluation measure is of the smaller-the-better type (e.g., the cost), the normalized measure is calculated by:

$$x^*_y = \frac{\max_{i} x_{ij} - x_y}{\max_{i} x_{ij} - \min_{i} x_{ij}}$$ \hspace{1cm} (5.4)

(c) If the evaluation measure is of the nominal-the-best type, and the target value is selected as $x_{obj}$, the normalized measure is calculated by:

$$x^*_y = \frac{|x_y - x_{obj}|}{\max_{i} x_{ij} - x_{obj}}$$ \hspace{1cm} (5.5)

The standard series should be converted into

$$A^*_0 = (x^*_0, x^*_1, \ldots, x^*_j, \ldots, x^*_n)$$ in the same manner.

3. Obtain the differences between the comparative series and the standard series.

To discover the degree of the grey relationship, the differences, $\Delta_0$, between the normalized decision matrix $K$ and the normalized standard series $A^*_0$ are achieved by:
4. Calculate the grey relational coefficients.

The grey relational coefficients, \( \gamma_{ij} \), indicate the contiguous grades between the comparative and standard series. A relational coefficient with higher value represents a closer relationship with the best evaluation measure considering all design candidates. The grey relational coefficient is calculated by:

\[
\gamma_{ij} = \frac{\Delta_{\text{min}} + \zeta \Delta_{\text{max}}}{\Delta_{ij} + \zeta \Delta_{\text{max}}}
\]

(5.7)

Where \( \Delta_{\text{max}} \) and \( \Delta_{\text{min}} \) are obtained by:

\[
\Delta_{\text{max}} = \max_i \max_j \Delta_{ij}
\]

(5.8)

\[
\Delta_{\text{min}} = \min_i \min_j \Delta_{ij}
\]

(5.9)

\( \zeta \) is called a distinguished coefficient, only affecting the relative value without changing the priority. Generally, \( \zeta \) is selected as 0.5 (Chang, 1996).

5. Determine the degree of relation with the standard series.

To achieve the degree of relation with the standard series (i.e., the ideal one), the weighting factors of the evaluation measures must first be decided. These weighting factors can be determined by expert experience or marketing strategies in the firm. The degree of relation with the standard series for a design candidate is calculated by:
\[ \Gamma_{0i} = \sum_{j=1}^{n} [w_j \times \gamma_{0j}] \]  

where \( w_j \) is the weighting factor for the \( j \)-th evaluation measure satisfying:

\[ \sum_{j=1}^{n} w_j = 1 \]

6. Prioritize the design candidates.

From the degrees of relation between the comparative and standard series, the design candidates can be prioritized. The design candidate with a larger \( \Gamma_{0i} \) can better satisfy the requirements considering different product life-cycle aspects.

This grey relational analysis approach treats each design candidate as a comparative series. The degree of relation between the comparative and standard series for each design candidate is then calculated. At the end, the best design candidate can be selected based on the rankings of all the design candidates.

5.4 Summary

A new method to evaluate design candidates in adaptable design is introduced in this work using the grey relational analysis approach. In this research, the different design candidates created in adaptable design are evaluated by different life-cycle evaluation measures including specific product adaptability, part cost, assembly costs, and operationability of customers. The grey analysis approach is used in this work for
prioritizing different design candidates considering different evaluation measures. Section 5.2 discussed evaluation measures of design candidates in adaptable design. Section 5.3 introduced the method to prioritize different design candidates in adaptable design using the grey relational analysis approach.

The next chapter will present two case studies which are designed according to the introduced design methodology and design process given in Chapter 4. These case studies are also used to demonstrate the effectiveness of evaluation method given in this chapter to select the best design candidate.
CHAPTER 6: CASE STUDIES

6.1 Introduction

This chapter provides two case studies to illustrate the effectiveness of adaptable design method in the product development. The goal of the first case study, given in Section 6.2, is to redesign a series of transportation vehicles by employing the design process for product adaptability. This case study mainly focuses on how to generate the conceptual design by following the design process and guidelines which were discussed in Chapter 4. The second case study, given in Section 6.3, focuses on the redesign of a stand mixer to make it adaptable for other functions found in a blender and a meat grinder. In this case study, 2 distinct design configurations with 8 product candidates are generated. The effectiveness of the introduced method for evaluating adaptable product candidates is also demonstrated through this case study. Section 6.4 gives a summary of this chapter.

6.2 Case Study 1: Design of Electric Vehicles

To illustrate the effectiveness of the introduced design process for product adaptability, this case study for designing transportation vehicles is given in this section. This case study focuses on redesign of a series of transportation vehicles which are available in market. The existing products, however, do not provide any adaptability. These vehicles are used for short-distance off-highway transportation applications.
6.2.1 Description of the Products

Five different products, including short-distance shuttle buses with 8 seats and 14 seats, inner city light duty trucks with box and flat platforms, and a baggage mover as shown in Figure 6.1, were selected for this case study.

Figure 6.1: Electric vehicles used in this case study (courtesy of DFEV)

The short-distance shuttle buses are used to transport passengers in parks, communities, campuses, airports, etc. The shuttle buses have two types of configurations, 8 seats and 14 seats, to be used in different places. The inner city light duty truck with box platform is used to deliver cargos in the city area. The light duty truck with flat platform is used to deliver parts and products in the factories and workshops. The baggage dragger vehicle is used to transport baggage using trailers in airports and train stations.

These five products used in this case study are analyzed based upon the architectures, geometric parameters, and performance measures of these products. The obtained
information is then used in the following design process for redesigning the adaptable electric vehicle.

The problems of these five products are identified as follows:

1. The vehicles with similarly configurations require different components and assemblies to be manufactured at the assembly plant.

2. Although the requirements of the users may change over time, the vehicles cannot be reconfigured to satisfy these different requirements.

3. It is difficult to improve the design by replacing the existing components with newly designed components. In addition, the reuse of components in other vehicles is impossible.

6.2.2 The Design Process

In this case study, the methodology of design for product adaptability is used to redesign these short-distance off-highway transportation vehicles.

*Function Modeling*

According to the mission statement which is derived from the analysis results of the above five products and a list of customer requirements, the solutions are generated by designers based on the requirements of design functions. For instance, the first level of requirements is for achieving the basic objective: development of the short-distance off-highway transportation vehicles. The electric vehicle is definitely the best solution.
Due to the usage of electric vehicle, the products can be designed as short range shuttle bus, inner city delivery truck with cargo box, factory delivery truck and baggage mover. All of the selected types of electric vehicles belong to light duty vehicles. Since all of them use the same driving system and control systems, these electric vehicles can be developed by using a shared platform. In this case, the functions of above 5 vehicles, such as personnel transportation, cargo transportation, and trailer transportation, are identified as the fundamental FRs in the redesign.

The functional requirement decomposition process is repeated again and again to create detailed solutions level by level to establish the trees of functional requirements (FRs) and design parameters (DPs). Figure 6.2 shows the trees of FRs and DPs at first two levels. The detailed results of individual products are shown in Figures 6.3-6.6.

![Figure 6.2: The trees of FRs and DPs (first two levels)](image-url)
Figure 6.3: The detailed levels of FRs and DPs trees for modeling the shuttle bus with 8 seats

Figure 6.4: The detailed levels of FRs and DPs trees for modeling the light duty truck with a box platform
Figure 6.5: The detailed levels of FRs and DPs trees for modeling a light duty truck with a flat platform

Figure 6.6: The detailed levels of FRs and DPs trees for modeling a baggage mover vehicle
According to Chapter 4, the relations between the functional requirements and the design parameters of each possible solution can be modeled by one design matrix. For example, the relations between FRs and the DPs of a shuttle bus can be modeled by:

\[
\begin{align*}
\{\text{FR}_{13}\} &= \begin{bmatrix} X & 0 & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_{13}\} \\
\{\text{FR}_{15}\} &= \begin{bmatrix} X & X & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_{15}\} \\
\{\text{FR}_{11}\} &= \begin{bmatrix} X & X & X & 0 & 0 \end{bmatrix} \{\text{DP}_{11}\} \\
\{\text{FR}_{12}\} &= \begin{bmatrix} X & 0 & 0 & X & 0 \end{bmatrix} \{\text{DP}_{12}\} \\
\{\text{FR}_{14}\} &= \begin{bmatrix} X & 0 & 0 & 0 & X \end{bmatrix} \{\text{DP}_{14}\}
\end{align*}
\] (6.1)

The FRs and DPs in Eq. (6.1) are given in Figure 6.3. Since FR11 is “provide traction”, it can be decomposed into FR111 “provide motion” and FR112 “transmit motion”. The relations between FR111 and FR112 are independent of each other. So they can be modeled by Eq. (6.2).

\[
\begin{align*}
\{\text{FR}_{111}\} &= \begin{bmatrix} X & 0 \end{bmatrix} \{\text{DP}_{111}\} \\
\{\text{FR}_{112}\} &= \begin{bmatrix} 0 & X \end{bmatrix} \{\text{DP}_{112}\}
\end{align*}
\] (6.2)

In the same way, the rest of sub-FRs in Figure 6.3 can be modeled as follow:

\[
\begin{align*}
\{\text{FR}_{131}\} &= \begin{bmatrix} X & 0 \end{bmatrix} \{\text{DP}_{131}\} \\
\{\text{FR}_{132}\} &= \begin{bmatrix} 0 & X \end{bmatrix} \{\text{DP}_{132}\}
\end{align*}
\] (6.3)

\[
\begin{align*}
\{\text{FR}_{151}\} &= \begin{bmatrix} X & 0 & 0 \end{bmatrix} \{\text{DP}_{151}\} \\
\{\text{FR}_{152}\} &= \begin{bmatrix} 0 & X & 0 \end{bmatrix} \{\text{DP}_{152}\} \\
\{\text{FR}_{153}\} &= \begin{bmatrix} 0 & 0 & X \end{bmatrix} \{\text{DP}_{153}\}
\end{align*}
\] (6.4)

Since the other types of electric vehicles are designed to use the same structure as the shuttle bus, the design matrices of those products are similar to those given in Eqs. (6.1-6.4).
Adaptable Platform/Modular Design

Based on the information of DPs created from the previous step, the product architecture and interactions among modules can be generated by considering the modularity of the product using the four-step process method (Ulrich, 1995) which has been introduced in Chapter 4. The first step is to create a schematic of the product by laying out the functional elements to represent the designer's understanding about the product. For example, Figure 6.7 shows the functional elements of the designed shuttle bus.

![Figure 6.7: The functional elements of a shuttle bus](image)

And then, the elements of the products are grouped into modules following the design guidelines. These modules form the assemblies of the product. And the dependency
relations among these modules are initially described by different types of lines to represent different types of dependency relations. Figure 6.8 shows the clustered functional elements of the shuttle bus.

Figure 6.8: The clustered functional elements of the shuttle bus

After the clustered functional structure has been developed, sketches should be created for modeling alternative layouts of the product modules. Iteration is also required during this step. Figure 6.9 illustrates the rough geometric layouts of the shuttle bus chassis.
Figure 6.9: The rough geometric layouts of the shuttle bus

Four chassis configurations are created by combining alternative modules. These layouts were created after a number of iterations.

When the rough geometric layout has been created, interactions between modules in the layout can be finally defined. The information of interactions will be used in the phase of adaptable interface design.

At the last, the conceptual result of product candidate can be modeled by an AND-OR tree based on the structures of product. The AND-OR tree structure is used to model the relationships among sub-structures with AND and OR relations. The customizable modules and upgradeable modules in the AND-OR tree are described by the symbols of C and U, respectively. For example, Figure 6.10 shows the AND-OR relationships among sub-structures in the design of the shuttle bus with C and U indicating the customizable modules and upgradeable modules, respectively.
Adaptable Interface Design

The interface design is carried out by designing the locking, release, and safety mechanisms to satisfy the key features such as convenience, high reliability, low cost, maximum generality, and self-alignment. Many types of interfaces are designed in this case study under several guidelines for accommodating different types of modularity architectures. Figure 6.11 illustrates the connector between two parts of frames.
Concept Design Evaluation

By following the guidelines and design process introduced in Chapter 4, the design engineers may achieve different design configurations, which all are adaptable and fulfill the design requirements. In this example, only one design configuration has been achieved for simplifying the design process.

Detail Design

Following the product architecture design, the result of the detail design is the complete design model with components and assemblies ready for manufacturing. This phase of design process includes industry design, engineering design analysis, dynamic analysis, and so on. Many CAD/CAM/CAE software systems are used for detail design. Figure 6.12 shows the parts and assembly of the chassis of the shuttle bus. Figure 6.13 gives the total assembly of the shuttle bus. Figure 6.14 presents the other types of vehicles based on the design of the shuttle bus.
Figure 6.12: The chassis assembly of the shuttle bus

Figure 6.13: The total assembly of the shuttle bus

Figure 6.14: The other types of vehicles based on the design of shuttle bus
For demonstrating this redesign, a 1:4 scale model has been built in this research using a Stratasys FDM rapid prototyping machine. By configuring the segregated frames and bodies, five different types of vehicles can be changed from one into others. Figure 6.15 shows two vehicle configurations by this 1:4 scale model. Figure 6.16 shows the segregated frames and body parts of this model.

Figure 6.15: The 1:4 scale model of the shuttle bus and light duty truck

Figure 6.16: The segregated frames and body parts of the 1:4 scale model
6.2.3 Results of Redesign

The final solution is achieved at the end of the design process. Figure 6.14 shows the five different types of vehicles created in this redesign. This new adaptable product provides the following features.

1. The chassis is segmented into many modules to form different configurations.

2. Configurations of the chassis can be changed to satisfy requirements of different users.

3. The chassis components are linked by common interface components.

4. Different bodies are used when different chassis configurations are selected.

5. The existing components of this vehicle can be replaced by new components with better functions and features.

Five different products in the new design are created from the same design and can be modified from one type into others for many different applications requiring different configurations of the product. The adaptation of these vehicles based on requirements of customers also requires the minimum effort because of the replacement parts with convenient interfaces. The newly designed vehicle can also be easily upgraded and customized to extend service time and be adapted to satisfy the user needs. For instance, the type of electric motor in the driving system can be changed. Three types of DC motors with different power outputs can be chosen by customers.
6.3 Case Study 2: Design of a Stand Mixer

Various electric-motor-driven based small appliances are used for processing different types of foods in the kitchen. These appliances include stand mixers, blenders and meat grinders, as shown in Figure 6.17.

![Figure 6.17: Electric-motor-driven based food appliances (courtesy of KitchenAid, Rival and Kitchworks)](image)

Some of these small appliances are used frequently in most homes. Since most of them have similar power driven and control systems, considerable redundancy functions can be found in these food processing appliances.

This case study focuses on the redesign of a stand mixer to make it adaptable for other functions found in a blender and meat grinder. The design objective and forecast information of probabilities to adapt the stand mixer to the adaptable functions are summarized in Figure 6.18. During the design process, 2 distinct design configurations with 8 product candidates are generated. The introduced evaluation method given in Chapter 5 is used to integrate the different evaluation measures for prioritizing different product candidates with different fundamental and adaptable functions.
6.3.1 The Trees of FRs and DPs

Since the detailed design process was illustrated in the first case study, the second case study only presents the results of major design phases. Two design configurations have been generated in this redesign of stand mixer with adaptable functions of meat grinder and blender. Both of the design configurations are created from the same function requirements (FRs), but some DPs of different design configurations are different. The trees of FRs and DPs and design matrices for different designs in different configurations are described as follows.

**Design Configuration 1**

Figure 6.19 shows the trees of FRs and DPs for modeling the stand mixer in design configuration 1.
Based on the axiomatic design, the design of stand mixer in design configuration 1 can be represented as:

\[
\begin{align*}
\{\text{FR}_4\} &= \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_4\} \\
\{\text{FR}_2\} &= \begin{bmatrix} X & X & 0 & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_2\} \\
\{\text{FR}_1\} &= \begin{bmatrix} X & X & X & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_1\} \\
\{\text{FR}_3\} &= \begin{bmatrix} X & X & X & X & 0 & 0 \end{bmatrix} \{\text{DP}_3\} \\
\{\text{FR}_5\} &= \begin{bmatrix} X & 0 & 0 & 0 & X & 0 \end{bmatrix} \{\text{DP}_5\} \\
\{\text{FR}_6\} &= \begin{bmatrix} X & X & X & X & X \end{bmatrix} \{\text{DP}_6\}
\end{align*}
\]  

(6.5)

\[
\begin{align*}
\{\text{FR}_{21}\} &= \begin{bmatrix} X & 0 \end{bmatrix} \{\text{DP}_{21}\} \\
\{\text{FR}_{22}\} &= \begin{bmatrix} 0 & X \end{bmatrix} \{\text{DP}_{22}\}
\end{align*}
\]  

(6.6)

\[
\begin{align*}
\{\text{FR}_{61}\} &= \begin{bmatrix} X & 0 & 0 \end{bmatrix} \{\text{DP}_{61}\} \\
\{\text{FR}_{62}\} &= \begin{bmatrix} 0 & X & 0 \end{bmatrix} \{\text{DP}_{62}\} \\
\{\text{FR}_{63}\} &= \begin{bmatrix} 0 & 0 & X \end{bmatrix} \{\text{DP}_{63}\}
\end{align*}
\]  

(6.7)
Figure 6.20 shows the tree of FRs and DPs for modeling meat grinder in design configuration 1.

The design of meat grinder in design configuration 1 can be represented as:

\[
\begin{align*}
\{\text{FR}_1\} &= \begin{bmatrix} X & 0 & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_1\} \\
\{\text{FR}_2\} &= \begin{bmatrix} X & X & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_2\} \\
\{\text{FR}_3\} &= \begin{bmatrix} X & X & X & 0 & 0 \end{bmatrix} \{\text{DP}_3\} \\
\{\text{FR}_4\} &= \begin{bmatrix} X & X & X & X & 0 \end{bmatrix} \{\text{DP}_4\} \\
\{\text{FR}_5\} &= \begin{bmatrix} X & X & X & X & X \end{bmatrix} \{\text{DP}_5\} \\
\{\text{FR}_{21}\} &= \begin{bmatrix} X & 0 \end{bmatrix} \{\text{DP}_{21}\} \\
\{\text{FR}_{22}\} &= \begin{bmatrix} 0 & X \end{bmatrix} \{\text{DP}_{21}\}
\end{align*}
\]
Figure 6.21 shows the FRs and DPs trees for modeling the blender in design configuration 1.

![Image of FRs and DPs trees](image)

**Figure 6.21: The FRs and DPs trees for modeling the blender in design configuration 1**

The design of blender in design configuration 1 can be represented as:

\[
\begin{align*}
\{\text{FR}_4\} &= \begin{bmatrix} X & 0 & 0 & 0 & 0 \end{bmatrix} \ \{\text{DP}_4\} \\
\{\text{FR}_2\} &= \begin{bmatrix} X & X & 0 & 0 & 0 \end{bmatrix} \ \{\text{DP}_2\} \\
\{\text{FR}_1\} &= \begin{bmatrix} X & X & X & 0 & 0 \end{bmatrix} \ \{\text{DP}_1\} \\
\{\text{FR}_3\} &= \begin{bmatrix} X & X & X & X & 0 \end{bmatrix} \ \{\text{DP}_3\} \\
\{\text{FR}_5\} &= \begin{bmatrix} X & 0 & 0 & 0 & X \end{bmatrix} \ \{\text{DP}_5\} \\
\{\text{FR}_6\} &= \begin{bmatrix} X & X & X & X & X \end{bmatrix} \ \{\text{DP}_6\}
\end{align*}
\]

(6.10)

\[
\begin{align*}
\{\text{FR}_{21}\} &= \begin{bmatrix} X & 0 \end{bmatrix} \ \{\text{DP}_{21}\} \\
\{\text{FR}_{22}\} &= \begin{bmatrix} 0 & X \end{bmatrix} \ \{\text{DP}_{21}\}
\end{align*}
\]

(6.11)

\[
\begin{align*}
\{\text{FR}_{51}\} &= \begin{bmatrix} X & 0 \end{bmatrix} \ \{\text{DP}_{51}\} \\
\{\text{FR}_{52}\} &= \begin{bmatrix} 0 & X \end{bmatrix} \ \{\text{DP}_{51}\}
\end{align*}
\]

(6.12)
Design Configuration 2

Figure 6.22 shows the FRs and DPs trees for modeling the stand mixer in design configuration 2.

The design of stand mixer in design configuration 2 can be represented as:

\[
\begin{bmatrix}
FR_4 \\
FR_2 \\
FR_1 \\
FR_3 \\
FR_5 \\
FR_6
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 & 0 & 0 \\
X & X & 0 & 0 & 0 \\
X & X & X & 0 & 0 \\
X & X & X & X & 0 \\
X & 0 & 0 & 0 & X \\
X & X & X & X & X
\end{bmatrix}
\begin{bmatrix}
DP_4 \\
DP_2 \\
DP_1 \\
DP_3 \\
DP_5 \\
DP_6
\end{bmatrix}
\]  \hspace{1cm} (6.13)

\[
\begin{bmatrix}
FR_{21} \\
FR_{22}
\end{bmatrix} =
\begin{bmatrix}
X & 0 \\
0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{21} \\
DP_{21}
\end{bmatrix}
\]  \hspace{1cm} (6.14)
Figure 6.23 shows the FRs and DPs trees for modeling the meat grinder in design configuration 2.

The design of meat grinder in design configuration 2 can be represented as:

\[
\begin{aligned}
\begin{bmatrix}
FR_{61} \\
FR_{62} \\
FR_{63}
\end{bmatrix} &=
\begin{bmatrix}
X & 0 & 0 & 0 & 0 \\
0 & X & 0 & 0 & 0 \\
0 & 0 & 0 & X & 0
\end{bmatrix}
\begin{bmatrix}
DP_{61} \\
DP_{62} \\
DP_{63}
\end{bmatrix}
\end{aligned}
\]  (6.15)

Figure 6.23: The FRs and DPs trees for modeling the meat grinder in design configuration 2

The design of meat grinder in design configuration 2 can be represented as:

\[
\begin{aligned}
\begin{bmatrix}
FR_{4} \\
FR_{2} \\
FR_{1} \\
FR_{3} \\
FR_{5}
\end{bmatrix} &=
\begin{bmatrix}
X & 0 & 0 & 0 & 0 \\
X & X & 0 & 0 & 0 \\
X & X & X & 0 & 0 \\
X & X & X & X & 0 \\
X & X & X & X & X
\end{bmatrix}
\begin{bmatrix}
DP_{4} \\
DP_{2} \\
DP_{1} \\
DP_{3} \\
DP_{5}
\end{bmatrix}
\end{aligned}
\]  (6.16)
The design of blender in design configuration 2 can be represented as:

\[
\begin{align*}
\{\text{FR}_1\} & = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_1\} \\
\{\text{FR}_2\} & = \begin{bmatrix} X & X & 0 & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_2\} \\
\{\text{FR}_3\} & = \begin{bmatrix} X & X & X & 0 & 0 & 0 \end{bmatrix} \{\text{DP}_3\} \\
\{\text{FR}_4\} & = \begin{bmatrix} X & X & X & X & 0 & 0 \end{bmatrix} \{\text{DP}_4\} \\
\{\text{FR}_5\} & = \begin{bmatrix} X & 0 & 0 & 0 & X & 0 \end{bmatrix} \{\text{DP}_5\} \\
\{\text{FR}_6\} & = \begin{bmatrix} X & X & X & X & X & X \end{bmatrix} \{\text{DP}_6\}
\end{align*}
\] (6.18)

\[
\begin{align*}
\{\text{FR}_{21}\} & = \begin{bmatrix} X & 0 \end{bmatrix} \{\text{DP}_{21}\} \\
\{\text{FR}_{22}\} & = \begin{bmatrix} 0 & X \end{bmatrix} \{\text{DP}_{21}\}
\end{align*}
\] (6.19)
\[
\begin{bmatrix}
FR_{51} \\
FR_{52}
\end{bmatrix} =
\begin{bmatrix}
X & 0 \\
0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{51}
\end{bmatrix}
\tag{6.20}
\]

6.3.2 Two Design Configurations

By conducting design considering product adaptability following the adaptable design guideline introduced in the Chapter 4, two design configurations are identified to fulfill the requirements of a stand mixer with the potential to be adapted to other types of food processing appliances.

The first design configuration, as shown in Figure 6.25, provides the functions of a stand mixer together with the functions of a blender and meat grinder. The second design configuration, as shown in Figure 6.26, also provides the functions of a stand mixer together with the functions of a blender and meat grinder. But the concepts of these two design configurations are different.

For the first design configuration, when only the function of the stand mixer is selected as the fundamental function of the product and the functions of a blender and meat grinder are selected as adaptable (optional) functions of the product, the part and assembly costs of this product are usually low, compared with a product with all 3 functions as the fundamental functions. The adaptability of a product with all the 3 functions is high, since no extra efforts are required to achieve any of the required food processing functions.
In this case study, 4 product candidates with different fundamental and adaptable functions are selected considering design configuration 1. In the same way, 4 product candidates with different fundamental functions and adaptable functions are selected considering design configuration 2. These 8 product candidates are summarized in Table 6.1. For example, the function of stand mixer is a fundamental function of product candidate 1. The rest two functions need to be adapted in the future.

The product candidates can also be described by AND-OR trees for modeling the detailed design information. For example, Figures 6.27 and 6.28 show the AND-OR tree structures of product candidate 1 and 2, respectively, based on design configuration 1.
Table 6.1: Product candidates with different fundamental and adaptable functions

<table>
<thead>
<tr>
<th>Design Configuration</th>
<th>Candidate</th>
<th>Stand Mixer</th>
<th>Grinder</th>
<th>Blender</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Configuration 1</td>
<td>Candidate 1</td>
<td>✓</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td></td>
<td>Candidate 2</td>
<td>✓</td>
<td>o</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Candidate 3</td>
<td>✓</td>
<td>✓</td>
<td>o</td>
</tr>
<tr>
<td></td>
<td>Candidate 4</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Design Configuration 2</td>
<td>Candidate 5</td>
<td>✓</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td></td>
<td>Candidate 6</td>
<td>✓</td>
<td>o</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Candidate 7</td>
<td>✓</td>
<td>✓</td>
<td>o</td>
</tr>
<tr>
<td></td>
<td>Candidate 8</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Note: ✓ indicates the function is a fundamental function in the candidate. O indicates the function is an adaptable function in the candidate.

Figure 6.27: The AND-OR tree structure of product candidate 1
Design candidate 2

Cu
AC electric motor
Power cord
Motor controller
Reducer with two output shafts
Frames and cover
5 Quart mixing bowl
Flat beater
Wire whip
Dough hook
Cap
Blade

U
Super blade
Ice crusher blade
200 watts
240 watts
360 watts
5 speed
10 speed
White color
Silver color
Red color

5.3.3 Four Measures for Evaluating the Adaptable Designs

In this work, specific product adaptability, total part cost, total assembly cost, and operation ability are selected as the evaluation measures considering design, manufacturing and operation life-cycle aspects of the products.

Specific Product Adaptability

Adaptability of a product represents its capability of being adapted with additional functions, which are usually initiated by changes in market demand, customer preferences, the operating environment of the product, and the reuse of components of a product after it retires.
In this case study, the probabilities of using different food processing functions are identified in advance as:

\[ Pr(\text{Stand Mixer}) = 100\% \]
\[ Pr(\text{Grinder}) = 20\% \]
\[ Pr(\text{Blender}) = 100\% \]

Table 6.2 shows the costs of parts for design configuration 1. When the function of the stand mixer is selected as the fundamental function of the product (i.e., candidate 1 in Table 6.1), the total part cost for this product is then calculated as $56. Based on the stand mixer in design configuration 1, the costs for achieving the functions of a meat grinder, and blender are identified as $10, and $8, respectively.

**Table 6.2: The individual part list for design configuration 1**

<table>
<thead>
<tr>
<th>No.</th>
<th>Part</th>
<th>Unit Cost ($)</th>
<th>Stand Mixer</th>
<th>Meat Grinder</th>
<th>Blender</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor</td>
<td>15(3)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>2</td>
<td>Controller</td>
<td>10(2)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>C,U</td>
</tr>
<tr>
<td>3</td>
<td>Reduce Gear</td>
<td>5</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Frame</td>
<td>10</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Bowl</td>
<td>10</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Flat Beater</td>
<td>2</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Wire Whip</td>
<td>2</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Dough Hook</td>
<td>2</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Grinder</td>
<td>10</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Cap</td>
<td>3</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Blade</td>
<td>5(2)</td>
<td></td>
<td></td>
<td>✓</td>
<td>U</td>
</tr>
</tbody>
</table>

Note: C indicates this part is selected as customization part  
U indicates this part is selected as upgradeable part  
() indicates the cost to provide the upgrading or customization function  

Table 6.3 gives the costs of parts for design configuration 2. For product candidate 5 from Table 6.1, the cost of the fundamental functions of the stand mixer is calculated as $54. Based on the stand mixer in design configuration 2, the cost to achieve the adaptable
Table 6.3: The individual part list for design configuration 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Part</th>
<th>Unit Cost ($)</th>
<th>Stand Mixer</th>
<th>Meat Grinder</th>
<th>Blender</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor</td>
<td>15</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>Controller</td>
<td>8</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>Reduce Gear</td>
<td>5</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>Frame</td>
<td>10</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>Bowl</td>
<td>10</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Glass Cup</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>7</td>
<td>Flat Beater</td>
<td>2</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Wire Whip</td>
<td>2</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Dough Hook</td>
<td>2</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Grinder</td>
<td>10</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Cap</td>
<td>3</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Blade</td>
<td>5</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Note: C indicates this part is selected as customization part
U indicates this part is selected as upgradeable part

The extendibility of function of meat grinder and blender are calculated as $10 and $16, respectively. Assume the costs for creating new products of meat grinder and blender are selected as $35, and $60, respectively.

The extendibility of candidate 1 is then calculated using Eq. (3.2).

\[ E(P_1) = 100\% \cdot (1 - 0) + 20\% \cdot \left(1 - \frac{10}{35}\right) + 100\% \cdot \left(1 - \frac{8}{60}\right) = 2.01 \]

For product candidate 2 from Table 6.1, the extendibility is calculated by:

\[ E(P_2) = 100\% \cdot (1 - 0) + 20\% \cdot \left(1 - \frac{10}{35}\right) + 100\% \cdot (1 - 0) = 2.14 \]

The extendibilities of all other candidates for design configuration 1 and 2 can be calculated in the same manner.

From Tables 6.2 and 6.3, we can find some parts are selected as upgradeable parts and customizable parts. The cost to upgrade or customize the current part to another part is
given in a bracket and modeled using the unit cost. In this case study, we assume that all of the selected parts will be upgraded or customized in the future.

The upgradeability of candidate 1 is then calculated using Eq. (3.4).

\[
U(P_1) = 100\% \cdot (1 - \frac{3}{12}) + 100\% \cdot (1 - \frac{2}{8}) = 1.5
\]

For product candidate 2 given in Table 6.1, the upgradeability is calculated by:

\[
U(P_2) = 100\% \cdot (1 - \frac{3}{12}) + 100\% \cdot (1 - \frac{2}{8}) + 100\% \cdot (1 - \frac{2}{3}) = 1.8
\]

The upgradeabilities of all other candidates for design configuration 1 and 2 can be calculated in the same manner.

Since some parts are selected as both the upgradeable parts and the customizable parts, they can use the same interfaces to be upgraded or to be customized. If the interface cost has been calculated considering the upgradeability, the cost for customization of the same part will be selected as 0, because both measures are achieved using the same interface. In this case study, the customization costs for frames and covers are 0s, since only the colors of the frame and the cover are customized.

The customizability of candidate 1 is then calculated using Eq. (3.6).

\[
C(P_1) = 100\% \cdot (1 - \frac{0}{12}) + 100\% \cdot (1 - \frac{0}{8}) + 100\% \cdot (1 - \frac{0}{10}) = 3.0
\]

The customization abilities of all other candidates for design configurations 1 and 2 can be calculated in the same manner.
Table 6.4: The results about extendibility, upgradeability, and customizability

<table>
<thead>
<tr>
<th>Design Configuration</th>
<th>Candidate</th>
<th>Extendibility</th>
<th>Upgradeability</th>
<th>Customizability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Configuration 1</td>
<td>Candidate 1</td>
<td>2.01</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Candidate 2</td>
<td>2.14</td>
<td>1.8</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Candidate 3</td>
<td>2.07</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Candidate 4</td>
<td>2.20</td>
<td>1.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Design Configuration 2</td>
<td>Candidate 5</td>
<td>1.86</td>
<td>0.75</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Candidate 6</td>
<td>2.13</td>
<td>0.75</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Candidate 7</td>
<td>1.93</td>
<td>0.75</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Candidate 8</td>
<td>2.20</td>
<td>0.75</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The results of extendibility, upgradeability and customizability of all the 8 product candidates are summarized in Table 6.4.

To use above three different evaluation measures, these measures should be converted into dimensionless evaluation measures in advance. The normalized measure for extendibility of functions, the upgradeability of modules and customizability of components are calculated by Eq. (3.7), Eq. (3.8) and Eq. (3.9), respectively.

These three values can then be combined into an overall specific product adaptability index in the weighted-sum formulation. The specific product adaptability index of i-th product candidate is calculated by Eq. (3.10):

\[
A(P)_i = \frac{I_E \ast NE(P)_i + I_U \ast NU(P)_i + I_C \ast NC(P)_i}{I_E + I_U + I_C}
\]

In this case, the weighting factor of each evaluation measure is defined equally as 33.3%, because extendibility of functions, upgradeability of modules, and customizability of components are in the same important level of specific product adaptability. The adaptabilities of all the 8 product candidates are summarized in Table 6.5.
Total Part Costs

Total part cost for each product candidate is calculated by adding the costs of all parts of which the product is composed of. For example, the total part cost of candidate 1 is calculated by:

\[
C(P_1) = C(Motor) + C(Controller) + C(Reduce gear) + C(Frame) + C(Bowl) + C(Flat beater) + C(Wire whip) + C(Dough hook)
\]

\[= $15 + $10 + $5 + $10 + $2 + $2 + $2 = $56\]

The total part costs of other product candidates are calculated in the same way, as shown in Table 6.5.

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Adaptable (0-1)</th>
<th>Total Part Cost ($)</th>
<th>Assembly Cost ($)</th>
<th>Operationability (0-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidate 1</td>
<td>0.916</td>
<td>56</td>
<td>10</td>
<td>4.5</td>
</tr>
<tr>
<td>Candidate 2</td>
<td>0.991</td>
<td>64</td>
<td>10</td>
<td>4.5</td>
</tr>
<tr>
<td>Candidate 3</td>
<td>0.925</td>
<td>66</td>
<td>12</td>
<td>4.5</td>
</tr>
<tr>
<td>Candidate 4</td>
<td>1.000</td>
<td>74</td>
<td>12</td>
<td>4.5</td>
</tr>
<tr>
<td>Candidate 5</td>
<td>0.643</td>
<td>54</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Candidate 6</td>
<td>0.684</td>
<td>70</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Candidate 7</td>
<td>0.654</td>
<td>66</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Candidate 8</td>
<td>0.695</td>
<td>82</td>
<td>15</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of Value</th>
<th>Quantitative</th>
<th>Quantitative</th>
<th>Quantitative</th>
<th>Qualitative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Criteria</td>
<td>The larger the better</td>
<td>The smaller the better</td>
<td>The smaller the better</td>
<td>The larger the better</td>
</tr>
</tbody>
</table>

Assembly Costs

Assembly cost is the cost for all assembly activities. Different product architectures usually require different assembly costs. In this case study example, the assembly costs of the 8 selected product candidates are given in Table 6.5.
As more parts are used in a product, the assembly cost usually increases. Since the assembly activities do not require considerable effort in the process of manufacturing, the differences among assembly costs of different candidates are not significant. From Table 6.5, we can see product configuration 2 has a higher assembly cost compared with the design configuration 1, due to its complex architecture.

*Operationabilities*

The operationability of products is based on convenience of interface, degree of difficulty to adapt to different functions, and the feelings of customers. Operationabilities are rated on scales between 0 to 5, from totally unsatisfactory to totally satisfactory. The operationabilities of the 8 product candidates are also given in Table 6.5.

### 6.3.4 Selection of Weighting Factors for Different Evaluation Measures

The weighting factors of the four different evaluation measures are determined from expert experience and marketing strategies. These weighting factors are identified as given in Table 6.6. Since this research focuses on adaptable design, a high weighting factor is selected for the adaptability evaluation measure.

<table>
<thead>
<tr>
<th>Evaluation Measure</th>
<th>Weighting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptability</td>
<td>45%</td>
</tr>
<tr>
<td>Part Cost</td>
<td>20%</td>
</tr>
<tr>
<td>Assembly Cost</td>
<td>20%</td>
</tr>
<tr>
<td>Operationability</td>
<td>15%</td>
</tr>
</tbody>
</table>
6.3.5 Prioritization of Product Candidates

Prioritization of the product candidates using the grey relational analysis approach is conducted as follows:

1. Establish the decision matrix $D$.

$$D = \begin{bmatrix}
0.916 & 56 & 10 & 4.5 \\
0.991 & 64 & 10 & 4.5 \\
0.925 & 66 & 12 & 4.5 \\
1.000 & 74 & 12 & 4.5 \\
0.643 & 54 & 13 & 5.0 \\
0.684 & 70 & 13 & 5.0 \\
0.654 & 66 & 15 & 5.0 \\
0.695 & 82 & 15 & 5.0 \\
\end{bmatrix}$$

2. Obtain the standard series.

$$A_0 = [1 \ 54 \ 10 \ 5]$$

3. Generate the normalized decision matrix $K$ and standard series $A_0^*$.

$$K = \begin{bmatrix}
0.765 & 0.929 & 1.000 & 0.000 \\
0.975 & 0.643 & 1.000 & 0.000 \\
0.790 & 0.571 & 0.600 & 0.000 \\
1.000 & 0.286 & 0.600 & 0.000 \\
0.000 & 1.000 & 0.400 & 1.000 \\
0.115 & 0.429 & 0.400 & 1.000 \\
0.031 & 0.517 & 0.000 & 1.000 \\
0.146 & 0.000 & 0.000 & 1.000 \\
\end{bmatrix}$$

$$A_0^* = [1 \ 1 \ 1 \ 1]$$
4. Calculate the differences between the comparative and standard series.

\[
\Delta_0 =
\begin{bmatrix}
0.235 & 0.071 & 0.000 & 1.000 \\
0.025 & 0.357 & 0.000 & 1.000 \\
0.210 & 0.429 & 0.400 & 1.000 \\
0.000 & 0.714 & 0.400 & 1.000 \\
1.000 & 0.000 & 0.600 & 0.000 \\
0.885 & 0.571 & 0.600 & 0.000 \\
0.969 & 0.429 & 1.000 & 0.000 \\
0.854 & 1.000 & 1.000 & 0.000 \\
\end{bmatrix}
\]

\[\Delta_{\text{max}} = [1 1 1 1]\]

\[\Delta_{\text{min}} = [0 0 0 0]\]

5. Determine the grey relational coefficients.

\[
\gamma_0 =
\begin{bmatrix}
0.680 & 0.875 & 1.000 & 0.333 \\
0.952 & 0.583 & 1.000 & 0.333 \\
0.704 & 0.538 & 0.556 & 0.333 \\
1.000 & 0.412 & 0.556 & 0.333 \\
0.333 & 1.000 & 0.455 & 1.000 \\
0.361 & 0.467 & 0.455 & 1.000 \\
0.340 & 0.538 & 0.333 & 1.000 \\
0.369 & 0.333 & 0.333 & 1.000 \\
\end{bmatrix}
\]

6. Determine the degrees of relations with the standard series.

Using the weighting factors and Eq. (5.10), the degrees of relations for all the 8 product candidates are obtained as follow.

\[\Gamma_{01} = 0.731; \quad \Gamma_{02} = 0.795; \quad \Gamma_{03} = 0.586; \quad \Gamma_{04} = 0.693;\]

\[\Gamma_{05} = 0.591; \quad \Gamma_{06} = 0.497; \quad \Gamma_{07} = 0.478; \quad \Gamma_{08} = 0.449\]
Figure 6.29 shows the degrees of relations for 8 product candidates:

![Bar chart showing the degrees of relations for eight product candidates.]

**Figure 6.29: The degrees of relations for eight product candidates**

7. Prioritize the 8 product candidates.

From the ratings of the product candidates, candidate 2 is selected as the best one, considering all the relevant life-cycle evaluation measures. Compared with candidate 1, candidate 2 can provide one more often-used functions (i.e., blender) with minor additional cost. Compared with candidate 2, candidate 4 provides only 1 more function (i.e., meat grinder), which is seldom used, with considerable additional cost.

As the results, the product candidate 2 from the first design configuration has been chosen after the evaluation and prioritization. The selected best candidate can then be designed in details.
6.4 Summary

This chapter presented two case studies which are both designed according to the introduced design methodology and design process on how to achieve the product adaptability given in Chapter 4. Section 6.2 provided a case study on the redesign of transportation vehicles with product adaptability to illustrate the design method of major design phases: function modeling, adaptable platform/modular design, adaptable interface design, and detail design. Section 6.3 discussed the case study of redesigning a stand mixer. Two different design configurations were created and 8 product candidates were generated from those design configurations in the design process. This case study was used to demonstrate effectiveness of the evaluation method given in Chapter 5 to select the best product candidate by prioritizing different product candidates under different evaluation measures.
CHAPTER 7: CONCLUSIONS AND FUTURE WORK

7.1 Thesis Summary

The goal of this research is to develop a design methodology considering product adaptability and an evaluation method to prioritize design candidates created in adaptable design.

In the previous research, the adaptabilities in adaptable design were classified into design adaptability and product adaptability depending on which aspect is considered for adaptation (Gu, 2004). This thesis primarily focused on the issues considering product adaptability. The product adaptability was identified as the ability of the physical product to be adapted for various purposes. Product adaptabilities are classified into specific product adaptabilities and general product adaptabilities depending on whether forecast information for specific adaptations is available. Specific product adaptability was modeled by extendibility of functions, upgradeability of modules, and customizability of components. The measures of specific product adaptability were also developed in this research to evaluate the specific product adaptability quantitatively.

Designs considering specific product adaptability and general product adaptability were achieved by the designs of base platforms, add-on modules, variant modules, and adaptable interfaces. A design process for product adaptability was developed for creating the product design which can be adapted by the users and the manufacturers to extend its utilities. The design process for product adaptability was summarized into 5 design phases: function modeling, adaptable platform/modular design, adaptable interface
design, concept evaluation and detail design. The details of guidelines and methods in each of the design phases have also been developed.

During the design process, the function decomposition method in the axiomatic design approach (Suh, 2001) was employed for decomposing functional requirements (FRs) and generating design parameters (DPs). As the result, the trees for modeling the FRs and DPs were established to help the design engineers to achieve the adaptable platform/modular design. Adaptable platform/modular design was conducted to achieve various objectives such as upgrading, customization, and so on based on the functions of modules.

The thesis also proposed a new method to evaluate design candidates in adaptable design by using the grey relational analysis approach. The different design candidates created in adaptable design were evaluated by different life-cycle evaluation measures including specific product adaptability, part costs, assembly costs, and operationability of customers. The grey analysis approach was used in this research for prioritizing different design candidates considering different evaluation measures.

Two case studies were also conducted based on the introduced design methodology and design process on how to achieve the product adaptability. The first case study on the redesign of transportation vehicles with product adaptability was used to illustrate the design method of major design phases: function modeling, adaptable platform/modular design, adaptable interface design, and detail design. The second case study of redesigning a stand mixer was used to demonstrate the effectiveness of evaluation
method to select the best design candidate by prioritizing different design candidates under different evaluation measures.

7.2 Contributions

Contributions of this research are summarized as follows.

- A measure of specific product adaptability was developed based on the three evaluation measures: extendibility of functions, upgradeability of modules, and customizability of components.

- The design process for product adaptability was summarized into 5 phases: function modeling, adaptable platform/modular design, adaptable interface design, concept evaluation and detail design.

- Guidelines of design process for product adaptability were developed. Adaptable design for product adaptability using the methodology can be accomplished using these guidelines.

- A new method to evaluate and prioritize different design candidates in adaptable design was introduced based on the grey relational analysis approach. The different design candidates created in adaptable design were evaluated by different quantitative life-cycle evaluation measures.
7.3 Future Work

Although the introduced design process for product adaptability and evaluation method can be used to meet the research goals, some issues need to be further addressed in the future development. These issues are summarized as follows.

1. The current design process for product adaptability is documented as the design phases and steps. The design decisions are made under the proposed methods and guidelines to achieve the product adaptability. To create the design candidates and evaluate these candidates automatically, a software system needs to be developed.

2. In the evaluation model, four evaluation measures, specific product adaptability, total part cost, total assembly cost, and operationability of customers, are selected for evaluating design candidates. To make this evaluation model more effective, more types of evaluation measures, such as the compatibility of interfaces, complexity of the product (number of functional parts), should be considered in the model.

3. The two case studies primarily focused on conceptual design. New case studies considering both the conceptual design and detailed design need to be developed to test the effectiveness of the introduced methods.
REFERENCES


