2025-11-21

Adaptable Product Design Through Integrated Modelling, Evaluation, and Optimization

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Adaptable Product Design Through Integrated Modelling, Evaluation, and Optimization

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF DOCTOR OF PHILOSOPHY

GRADUATE PROGRAM IN MECHANICAL AND MANUFACTURING ENGINEERING

CALGARY, ALBERTA

NOVEMBER, 2025

Abstract

Contrary to traditional product design with predefined functions, an adaptable product is designed such that its structure can be modified during operation to meet new functional requirements. The design of adaptable products can extend their lifespans, thereby saving costs for customers and reducing the environmental impact by avoiding the manufacturing of unnecessary products. The objective of this research is to develop new methods for adaptable product design through integrated modelling, evaluation, and optimization.

First, a method is developed to incorporate the considerations of the adaptation process in addition to the product configuration for optimal adaptable product design. A procedure for the adaptation of an existing product is also introduced. Since large numbers of adapted design configurations and adaptation processes are usually considered in the optimization process, a new method is developed to improve the efficiency of optimization through the evaluation of information quality in branches of the AND-OR tree based on information entropy and pruning of the branches that are unlikely to lead to the optimal solution.

Second, a method is introduced for the design of new adaptable products that can be easily changed during operation stages to satisfy the new requirements. In this method, the generic product design is modelled by an AND-OR tree, considering alternative solutions of the original product design configurations, the adapted product design configurations, the product adaptation processes, and configuration/process parameters. Different feasible solutions are created through tree-based search. The optimal solution defined by its original product design configuration, adapted product design configuration, adaptation process, and configuration/process parameters is identified through multi-level optimization.

Third, a method is formulated to evaluate the general product adaptability, considering cases where the product adaptation requirements are not available at the design stage. In this evaluation method, various influencing factors in the product design modelling scheme, including adaptable and unadaptable components/sub-assemblies, components/sub-assemblies within modules, and uncertainties associated with components/sub-assemblies in product adaptation, are considered for calculating the general product adaptability. This new evaluation measure is employed in the development of an optimal adaptable product design method, considering cases with or without specific product adaptation requirements at the design stages.

Acknowledgements

First, I express my deepest gratitude to my PhD supervisor, Dr. Deyi Xue, for his valuable guidance, consistent support, and insightful mentorship throughout my doctoral journey. His dedication, patience, and profound expertise significantly shaped my research and academic growth, as well as my attitude toward life.

Second, I sincerely thank my supervisory committee members, Dr. Yiliu (Paul) Tu and Dr. Joseph Thekinen, whose constructive feedback, insightful comments, and thoughtful discussions greatly enhanced the quality of my research.

Third, I gratefully acknowledge the financial support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Alberta Graduate Excellence Scholarship (AGES) program, the PhD Excellence Scholarship from the Department of Mechanical and Manufacturing Engineering at the University of Calgary, and the Graduate Research Impact Excellence Award from the Schulich School of Engineering at the University of Calgary. Their generous support made this research possible.

Last but not least, my heartfelt appreciation goes to my wife, my son, my parents, my siblings, my parents-in-law, and my siblings-in-law for their unwavering encouragement, understanding, prayers, and continuous emotional support. Their belief in me and constant motivation were instrumental throughout this challenging yet rewarding journey.

Dedication

To my father, ***Dr. Hassoun Ragab Saad****, and my mother,* ***Ruqaia Hassan Mahmoud****, for their lifelong sacrifices, wisdom, and unconditional love that laid the foundation for all my accomplishments.*

To my beloved wife, ***Hiyam Khalil****, whose unwavering support, patience, and love have been the cornerstone of this journey.*

To my precious son, ***Houssam****, whose presence inspires me to strive for a better future.*

To my siblings, ***Abdulrahman****,* ***Heba****,* ***Ahmed****, and* ***Nada****, thank you for your encouragement, belief in me, and endless support.*

To my father-in-law, ***Hisham Haras Khalil****, and my mother-in-law,* ***Habab Gadoora Ahmed****, whose kindness, prayers, and encouragement have been deeply appreciated throughout this journey.*

To my siblings-in-law, ***Rihab****,* ***Hibat-Allah****, and* ***Khalid****, thank you for your support, positivity, and warm presence.*

This work is dedicated to all of you, with deepest gratitude and love.

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Chapter 1. Introduction

1.1. Background

Increasing competition in the global marketplace requires manufacturing enterprises to be responsive in developing products with better functionality, higher quality, lower cost, shorter development lead time, and increased environmental friendliness. Although advanced manufacturing technologies, such as computer numerically controlled (CNC) machining, robotics, computer aided design and manufacturing (CAD/CAM), and computer-integrated manufacturing (CIM), can partially address these challenges, advanced design technologies and tools are needed and considered critical, since important decisions are made in the early product design stage with respect to the product functionality, quality, manufacturability, cost, and environmental performance for the optimal design and development of products.

Development of adaptable products is considered as an effective approach to improve the global competitiveness of manufacturers (Gu et al. 2004). Adaptable products are designed to allow changes to their configurations and parameters during their operation stages to meet new customer requirements or operating conditions (Gu et al. 2004; Gu et al. 2009; Gu et al. 2024). The changes can involve modifications to the physical structure of a product to adjust its functionality. Adaptable design is an approach to achieve the designs of adaptable products to satisfy the changing requirements (Gu et al. 2009). Adaptable design was first introduced by Gu et al. (2004) as a design model associated with the product lifecycle concerns from sustainability point of view. When design requirements are modified as a result of changes in the customer requirements or the operating environment of a product or due to technological advancement (e.g., a computer requiring wireless communication in addition to an Ethernet cable), the manufactured product may no longer satisfy the new requirements. Either the existing design needs to be adapted to create a new design and its product, or the existing product needs to be adapted directly to satisfy the new requirements. The task to modify a product to satisfy new requirements is called product adaptation.

Design of adaptable products can reduce the number of needed products to save costs and respond quickly to changing customer requirements. Adaptable products are particularly valuable in environments where technology, consumer preferences, or regulations change frequently.

Instead of discarding or recycling a product when its functions cannot be restored through maintenance and repair work or when it no longer meets new requirements, the product can be modified by changing or reconfiguring some of its components and modules to achieve the desired new functions, allowing the product to remain useful over a longer period without needing to be completely replaced. This approach not only enhances the product's lifespan but also contributes to sustainability by reducing waste and demand for new resources and reduces costs for consumers, thus improving the competitiveness of the product in the marketplace.

Since the introduction of the adaptable product design concept, significant efforts have been devoted to research in this area (Gu et al. 2009; Gu et al. 2024). Many new methods have been developed to overcome the challenges primarily in design modelling, design evaluation, and design optimization. A primary goal of adaptable product design is to extend the functionality of a product. Therefore, the design of an adaptable product should be modelled in a way such that the product can be easily changed to deliver new functions. For modelling of adaptable product design, the AND-OR tree was often used to define the generic product design with multiple design candidates to satisfy the same design requirements (Xue 1997; Martinez and Xue 2018). The design of an adaptable product should be evaluated through measures in design. When multiple design candidates are created, the one with the best evaluation measure values is selected for production. For the design of an adaptable product, different configurations are required for different design functions. Various configurations should be designed in a way that allows changing from one configuration to another one with the minimal effort. Multi-level optimization was often employed to identify the optimal product design configuration and optimal parameter values for adaptable product design (Xue et al. 2012; Saad and Xue 2024). In addition to theoretical research, industrial applications, such as the design of an adaptable product platform for a heavy-duty gantry milling center to add new machining functions (Cheng et al. 2017a) and the design of an adaptable machine to coat liquid materials on new products with different shapes (Chen et al. 2018), have also been developed.

The current research on adaptable product design primarily focuses on identifying the optimal product design configurations and design parameters (Zhang et al. 2014a; Zhang et al. 2014b; Martinez and Xue 2018), while adaptation processes and their parameters have not been considered. However, when the efforts required for product adaptation processes are substantial, it becomes essential to consider not only the product design configurations but also the product

adaptation processes. The optimization method may become inefficient when large numbers of design candidates and process candidates are considered. In order to improve the optimization efficiency, a novel method is needed to reduce the number of design candidates and adaptation process candidates.

The process for adapting an existing product, compared with the creation of a new product from scratch, can result in savings in costs, thus making the product more competitive in the marketplace. In many cases, however, the efforts needed for adaptation of an existing product during its operation stage can be high since product adaptation was not considered during the design stage of that product. As a result, the existing product should be discarded, and a new product needs to be designed and manufactured. To solve this problem, methods for the design of new adaptable products that can be easily adapted to satisfy requirement changes should be developed.

Product adaptability was often used to evaluate the design solutions in adaptable product design. When the requirements for product adaptation are specific or can be predicted at the design stage, the product adaptability is called "specific product adaptability" (Gu et al. 2004; Li et al. 2008). When the requirements for product adaptation are not given or unpredictable at the design stage, the product adaptability is called "general product adaptability" (Fletcher et al. 2009). In the past, research on the evaluation of product adaptability primarily focused on the development of various measures to evaluate the specific product adaptability. Evaluation of the general product adaptability, however, faces challenges due to the unpredictable requirement changes. In real-world applications, products often encounter unanticipated changes in operating environment, user demands, regulatory requirements, or technological advancements that arise during their operation stages. Therefore, development of an effective measure to evaluate the general product adaptability for adaptable product design is needed.

1.2. Problem Statements

Despite the research efforts devoted to the design of adaptable products as a strategy for extending products' lifespans and reducing lifecycle costs, several critical challenges remain unaddressed in current research. Through extensive literature review, the following problems and requirements have been identified for optimal design of adaptable products.

(1) Adaptation processes have been overlooked in adaptable product design research. When both product design candidates and adaptation process candidates are considered, optimization method may become inefficient.

Adaptation processes can have significant contribution to the overall cost of product adaptation. When both product design candidates and adaptation process candidates are considered in the design of adaptable products, the solution space may expand significantly, leading to challenges in optimization efficiency.

- The current research activities on adaptable product design focused on identification of the optimal product design configurations and design parameters without consideration of product adaptation processes and process parameters. When significant effort is required in the product adaptation process, identification of both the optimal product design (i.e., design configuration and design parameters) and the optimal adaptation process (i.e., collection of operations and operation parameters) must be considered.
- Although the multi-level optimization method can be used to identify the optimal product design configuration, the optimal adaptation process, and the optimal values of design and process parameters, this method may not be efficient when large numbers of design candidates and process candidates are considered, particularly for optimization to identify both the optimal product design candidate and the optimal adaptation process candidate through search with the AND-OR tree.
- Several methods have been developed to prune branches of the AND-OR tree to improve optimization efficiency (Gadalla and Xue 2023). Since information entropy (Shannon 1948; Hayat et al. 2020) is effective to evaluate quality of information in solutions with uncertainties, it can be considered to evaluate the information quality in branches of the AND-OR tree, such that the branches with poor information quality are pruned to improve optimization efficiency. The method to evaluate the branches of an AND-OR tree based on information entropy has never been developed.
- The approach for adaptation of existing products (i.e., manufactured products) is important because it can extend their lifespans and play a crucial role in reducing environmental impact. Adaptation of existing products can be challenging since a systematic procedure for adapting

existing products has not been developed. Therefore, an appropriate procedure for adaptation of existing products needs to be developed.

(2) Design of the original product configuration before adaptation and design of the adapted product configuration after adaptation have not been considered together.

The design and adaptation process activities to change an existing product during its utilization stage and the design and adaptation process activities to create a new adaptable product that can be easily changed during its utilization stage are different. Identification of the original product design configuration before adaptation plays a more significant role in influencing the efforts for product adaptation. The currently developed methods for the design of adaptable products are not effective for simultaneous design of the original product configurations before product adaptation and the adapted product configurations after product adaptation.

- In the past, many methods have been developed for design considering either adaptation of the existing products (i.e., only the adapted product design configuration candidates were considered) or creation of the new adaptable products (i.e., only the original product design configuration candidates were considered). However, design methods considering both multiple candidates for the original product design configuration and multiple candidates for the adapted product design configuration simultaneously have not been developed.
- Although the AND-OR tree can be used to model the generic design and to create different design candidates through tree-based search, modelling of the generic design considering both the different candidates for the original product design configuration and the different candidates for the adapted product design configuration as well as the relevant product adaptation processes and design/process parameters has not been developed.

(3) The currently developed evaluation methods for the design of adaptable products are not effective for evaluating the general product adaptability when adaptation requirements are not specific.

When the specific requirements for product adaptation are not given or unpredictable at the design stage, the product should be designed with structures to accommodate for the unpredicted adaptation requirements. Although the general product adaptability considering relations among different components of the product in the product structure, that is modelled by a tree/graph, has

been introduced in the literature (Fletcher et al. 2009), the following problems and requirements that influence the general product adaptability have been identified.

- In the method by Fletcher et al. (2009), all the design nodes in a graph/tree were considered adaptable, implying that any component in that product can be changed. However, in real world, changes to some components are not allowed. For example, the RAMs of some laptop computers cannot be replaced or upgraded when they reach the end of their operational life.
- In the method by Fletcher et al. (2009), all the design nodes could be changed separately. In the real world, some components must be changed together. For example, the three-color toner cartridges for some printers are designed as single modules and must be replaced together even when the toner of only one color is run out.
- In the method by Fletcher et al. (2009), the probabilities of design node changes were not considered. In the real world, different components may have different chances to be changed due to the preferences of customers, the functions of components, and the constraints in product adaptation. For example, batteries from old cell phones have less chance of being replaced due to the availability of batteries and the needs of the users.

1.3. Research Objectives

The overall objective of this research is to develop an approach for the design of adaptable products through integrated modelling, evaluation, and optimization. Based on the discussions of the three problems stated in Section 1.2, the three objectives of this research are described as follows:

Objective 1: *Development of a method for improvement of optimization efficiency to identify the optimal product design and the optimal product adaptation process by initial evaluation of information quality in branches of an AND-OR tree based on information entropy*

This specific objective is composed of the following sub-objectives:

- Development of a modelling scheme to define the adapted design alternatives, the adaptation process alternatives, and parameters of design and process alternatives using an AND-OR tree

- Investigation of the relations among entropy measures of nodes with AND relations and OR relations in the AND-OR tree, and development of a method to calculate information entropy of a branch in the AND-OR tree
- Evaluation of the information quality in branches of the AND-OR tree, such that the branches with poor information quality are pruned to improve optimization efficiency
- Development of a systematic procedure for identification of the optimal adapted product design configuration, the optimal adaptation process, and the optimal values of configuration/process parameters for adaptation of an existing product

Objective 2: *Development of a method for the design of new adaptable products considering the original design configurations before adaptation, the adapted design configurations after adaptation, and the adaptation processes*

This specific objective is composed of the following sub-objectives:

- Development of a framework to integrate the tasks for adaptation of existing products and tasks for the design of new adaptable products in the same environment
- Development of a modelling scheme to define different candidates for the original product design configurations, the adapted product design configurations, the adaptation processes, and configuration/process parameters using AND-OR tree
- Development of a systematic procedure for identification of the optimal original design configuration, the optimal adapted design configuration, the optimal adaptation process, and the optimal values of configuration/process parameters for design of new adaptable product

Objective 3: *Development of a method to evaluate the general product adaptability based on the method developed by Fletcher et al. (2009) considering various factors that influence the general product adaptability for the design of adaptable products*

This specific objective is composed of the following sub-objectives:

- Development of a modelling scheme to define the generic product design AND-OR tree considering both adaptable design nodes and unadaptable design nodes, design nodes in modules, and adaptation probabilities of design nodes

- Development of a method to evaluate the general product adaptability of a design candidate solution considering the influence of adaptable and unadaptable nodes, design nodes in modules, and adaptation probabilities of design nodes
- Development of a systematic procedure for identification of the optimal adaptable product design solution with the best general product adaptability considering both cases without specific adaptation requirements and cases with specific adaptation requirements, and considering the influence of adaptable and unadaptable nodes, design nodes in modules, and adaptation probabilities of design nodes

1.4. Research Summary

This section summarizes the approaches developed in this thesis based on the problem statements and research objectives presented in Section 1.2 and Section 1.3, respectively.

(1) Development of a method for improvement of optimization efficiency to identify the optimal product design and the optimal product adaptation process by initial evaluation of information quality in branches of an AND-OR tree based on information entropy

In this research, both product design candidates and adaptation process candidates are considered for adaptation of existing products. A new optimization approach to identify both the adapted product design and the product adaptation process is developed with initial evaluation of information quality in branches of an AND-OR tree based on information entropy. In this approach, various candidates of design configurations and operation processes for adaptation of an existing product are modelled by an AND-OR tree with design and process nodes. Design and process nodes are further associated with design and process parameters. The different adapted design configuration solutions and product adaptation process solutions are created from the AND-OR tree through tree-based search. Optimization to identify the best adapted design and adaptation process is conducted at two levels: configuration/process optimization level and parameter optimization level. Information entropy is employed to evaluate the information quality of partial configuration/process candidates modelled as branches in the AND-OR tree to eliminate the branches that are unlikely to lead to the optimal solution for improvement of the optimization efficiency.

(2) Development of a method for the design of new adaptable products considering the original design configurations before adaptation, the adapted design configurations after adaptation, and the adaptation processes

In this research, a new method is developed to identify the original product design configuration, the adapted product design configuration, and the product adaptation process for the design of a new adaptable product. In this method, the generic adaptable product design considering alternative solutions of the original design configurations, the adapted design configurations, and the product adaptation processes is modelled by an AND-OR tree. Nodes of this tree are defined by unadaptable design nodes, adaptable design nodes, and adaptation process nodes. Design and process nodes are further associated with design and process parameters. The different original design configuration solutions, adapted design configuration solutions, and process solutions are created from the AND-OR tree through tree-based search. Solution of the adaptable design with the optimal original design configuration, adapted design configuration, and product adaptation process is identified through multi-level optimization (i.e., configuration/process optimization and parameter optimization).

(3) Development of a method to evaluate the general product adaptability based on the method developed by Fletcher et al. (2009) considering various factors that influence the general product adaptability for the design of adaptable products

In this work, a method is developed to evaluate the general product adaptability for the design of adaptable products, based on the method developed by Fletcher et al. (2009), considering influencing factors. In this method, in addition to the general product adaptability defined by comparison between the actual product architecture and its ideal segregated product architecture, influences of adaptable and unadaptable components/sub-assemblies, components/sub-assemblies in modules, and uncertainties of components/sub-assemblies in product adaptation are also considered for evaluation of the general product adaptability. The developed measure is integrated with the approach for design of new adaptable products considering cases without specific adaptation requirements and with specific adaptation requirements. The new measure is used to evaluate all the possible solutions to identify the one with the best general product adaptability value.

1.5. Thesis Structure

1.5.1. Thesis organization

The rest of this thesis is organized as follows.

In Chapter 2, a literature review is provided in the research areas relevant to this thesis, including modelling, evaluation, and optimization methods for the design of adaptable products. The characteristics of these existing methods are explained and discussed for a better understanding of the newly developed methods summarized in this thesis.

In Chapter 3, a method based on information entropy is developed to improve the optimization efficiency when large numbers of product design candidates and adaptation process candidates are considered. A systematic procedure for the adaptation of existing products during their operation stages is also explained.

In Chapter 4, a method is introduced to identify the optimal original design configuration, adapted design configuration, and adaptation process for design of a new adaptable product. In this method, a framework to integrate both the tasks of the design for adaptation of existing products and the tasks for the design of new adaptable products into the same environments is developed. A systematic procedure for the design of new adaptable products that can be easily changed during their operation stages is also explained.

In Chapter 5, a method is developed to evaluate the general product adaptability for the design of adaptable products considering the influencing factors of adaptable nodes and unadaptable nodes, nodes in modules, and probabilities of node adaptations. The developed new evaluation measure is employed in the development of a new adaptable product design approach, considering cases without or with specific requirements for product adaptations at the design stage.

In Chapter 6, the major contributions of this research are summarized. Potential improvements and challenges to be further investigated as future work are also discussed.

1.5.2. Relations among Chapters 3-5

Chapters 3-5 are organized in the sequences considering design scopes and adaptation requirements for adaptable product design as shown in Table 1.1.

Table 1.1. Relations among Chapter 3, Chapter 4, and Chapter 5

	Design scopes		**Adaptation requirements**	
	Design of the adapted product configuration	Design of the original product configuration	Specific adaptation requirements	General adaptation requirements
Chapter 3	✓		✓	
Chapter 4	✓	✓	✓	
Chapter 5	✓	✓	✓	✓

(1) Design scopes

Scopes of adaptable product design in this work are classified into the following two categories.

- *Design for adaptation of existing products*

  This type of design focuses on identification of the design solution for adaptation of an existing product (i.e., manufactured product). Multiple adapted product design solutions are usually created and evaluated for selection of the optimal one. An example for this type of design is to convert an existing internal combustion engine (ICE) car into an electric vehicle (EV). Different electric motors and batteries are considered for identification of the optimal adapted design of the electric vehicle.

- *Design of new adaptable products*

  The efforts for adaptation of existing products are usually high since product adaptation was not considered during the design stages. The approach for the design of new adaptable products can be used to solve this problem by creating new adaptable product designs that can be easily adapted during their operation stages. Multiple design candidates of the original product configuration before product adaptation are usually considered for selection of the optimal solution. For each of the original product design configurations, multiple solutions of the adapted product design configurations are also considered for selection of the optimal adapted product design configuration. An example of this type of design is to create a new adaptable ICE car for easy conversion into an EV.

In Chapter 3, only the design for adaptation of existing products is conducted considering multiple solutions of the adapted product design configurations. In Chapters 4 and 5, design of the

new adaptable products considering both multiple solutions of the original product design configurations and multiple solutions of the adapted product design configurations for each of the original product design configurations is carried out.

(2) Adaptation requirements for adaptable product design

In this work, product adaptation requirements for the design of adaptable products are classified into the following two categories, specific product adaptation requirements, and general product adaptation requirements, depending on whether adaptation requirements are given at the design stage.

- *Specific product adaptation requirements*

  Specific product adaptation requirements are given or can be predicted at the design stage. Design solutions can be evaluated considering the specific adaptation requirements by measures such as the specific product adaptability (i.e., cost saving percentage for adapting an existing product compared to creating a new one) (Gu et al. 2004), or the adaptation cost (i.e., the total cost required to convert a product from the original configuration to the adapted configuration).

- *General product adaptation requirements*

  The general product adaptation requirements are the ones that are unknown or unpredictable at the design stage. Even when the requirements for product adaptation are unpredictable at the design stage, products should also be designed with structures to accommodate for these unpredicted product requirements. Geneal product adaptability is such a measure to evaluate product adaptability without given specific product adaptation requirements. An example of general product adaptability was defined by comparing the current product architecture with the ideal (segregated) product architecture (Fletcher et al. 2009).

In Chapters 3 and 4, design with specific product adaptation requirements is considered. In Chapter 5, design with general product adaptation requirements is considered.

As stated earlier, in the design of adaptable products, many methods and tools have been developed to overcome the challenges primarily in design modelling, design evaluation, and

design optimization. Table 1.2. summarizes the main work carried out in Chapters 3-5 with respect to the key aspects of adaptable product design (i.e., modelling, evaluation, and optimization).

Table 1.2. Modelling, evaluation, and optimization aspects for adaptable product design in Chapters 3-5

Adaptable product design aspect	Chapter 3	Chapter 4	Chapter 5
Modelling	• Adapted product design configuration candidates • Product adaptation process candidates • Parameters of configuration/process	• Original product design configuration candidates • Adapted product design configuration candidates • Product adaptation process candidates • Parameters of configuration/process	• Original product design configuration candidates • Adapted product design configuration candidates • Parameters of configuration
Evaluation	• Specific product adaptability and Adaptation cost • Other evaluation measures (e.g., cost, performance) • Overall evaluation index considering multiple evaluation measures	• Specific product adaptability and Adaptation cost • Other evaluation measures (e.g., cost, performance) • Overall evaluation index considering multiple evaluation measures	• Specific product adaptability and Adaptation cost • General product adaptability • Other evaluation measures (e.g., cost, performance) • Overall evaluation index considering multiple evaluation measures
Optimization	• Information entropy of a branch in an AND-OR tree to improve optimization efficiency • Identification of the optimal solution with the adapted product configuration and the product adaptation process • Identification of the optimal configuration and process parameter values	• Identification of the optimal solution with the original product configuration, adapted product configuration, and product adaptation process • Identification of the optimal configuration and process parameter values	• Identification of the optimal solution with the original product configuration and adapted product configuration • Identification of the optimal configuration parameter values

Chapter 2. Literature Review

2.1. Adaptable Products

This section introduces the concept of adaptable products. A brief overview for the process of adaptable product design is also provided, followed by a discussion of the key environmental and economic benefits for the design of adaptable products.

2.1.1. Introduction to adaptable products

Product competition in the global marketplace demands products manufactured with better functionality, higher quality, lower cost, shorter development lead time, and increased environmental friendliness (Gu et al. 2004). Increased demand for a greater choice of products has prompted many businesses to rethink their strategies to deliver more product possibilities while retaining production efficiency. Moreover, intense market competition is causing multiple conflicts among users, manufacturing enterprises, and society (Mabey et al. 2023). Users anticipate acquiring high-quality, personalized, and intelligent products at lower prices. Manufacturing enterprises consider the impact of production factors such as cost and efficiency. Meanwhile, society demands sustainability, minimal carbon emissions, and energy efficiency. The uncertainty, variability, and unpredictability of requirements, coupled with the limited availability and cost of material resources, and the potential for environmental pollution, are key issues in the product competition in the global marketplace (Mabey et al. 2023).

The traditional products are designed with predefined functions. Although maintenance and repair are often carried out to preserve these functions, product structure changes to achieve new functions are typically not allowed. Adaptable products are the ones that can be easily changed to satisfy new functional requirements during their utilization stages (Gu et al. 2004; Gu et al. 2009; Gu et al. 2024). The concept of adaptable product design was introduced by Gu et al. (2004) to improve the competitiveness of manufacturers by creating adaptable products, particularly mechanical products, that can be easily modified to satisfy changes in functional requirements, operation environments, and technology advancement during their operation stages. An example of an adaptable product is a laptop that can be adapted by replacing or upgrading its RAM. A cell

phone that can be adapted by changing its memory unit to store more data is another example of an adaptable product.

Product adaptability was usually used to evaluate the design of adaptable products (Gu et al. 2004; Cheng et al. 2011). The product adaptability is defined as the capability of a physical product to be adapted to satisfy the changed requirements. In adaptable product design, a new product is achieved by modifying the existing product, such as adding new components/modules, replacing or upgrading the existing components/modules with new ones, and reconfiguring the existing components/modules. The activity to modify a product to satisfy new requirements is called product adaptation. Product adaptation can be carried out either by the user or by a contractor requested by the user. Product adaptation is usually carried out through the following steps:

- Definition of new requirements
- Selection of the existing product
- Selection of the existing design corresponding to the existing product
- Creation of new design solution candidates for product adaptation through design adaptation
- Evaluation of the design solution candidates and identification of the best design solution candidate
- Change of the existing product through product adaptation to satisfy the new requirements

For a product to be adaptable, its design should also be adaptable. Willems et al. (2003) reported that the adaptability of a product at the end of its lifecycle is significantly influenced by its design. When design requirements are modified due to changes in the customer requirements or the operating environment of a product or advances in technology, the manufactured product may not be able to satisfy the new requirements. Either the existing design needs to be adapted to create a new design and its product, or the existing product needs to be adapted directly to satisfy the new requirements, as shown in Figure 2.1. Similar to product adaptation, the tasks to modify a design to satisfy new requirements are called design adaptation.

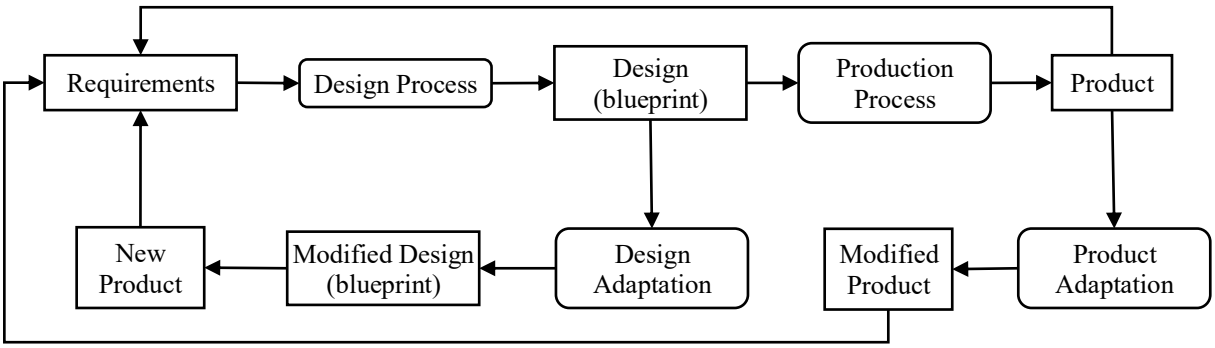


Figure 2.1. Design adaptation and product adaptation in adaptable design (Gu et al. 2009)

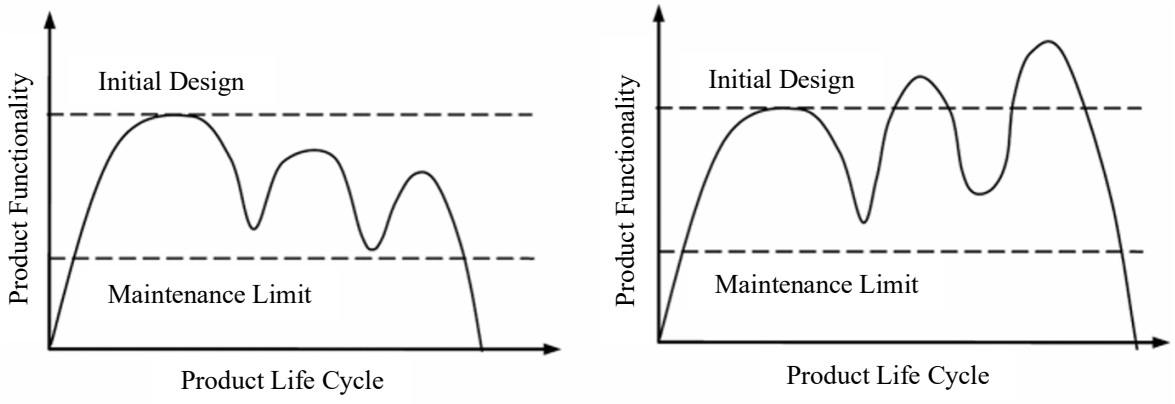
2.1.2. Benefits of adaptable product design

Adaptable product design has gained popularity in recent decades as a critical tool for lowering resource consumption and energy use, as well as environmental impact, while preserving or improving consumer satisfaction. In this section, the key advantages of adaptable product design are explored, highlighting its value for the users, the environment, and the economy.

Benefits for the users – Extended product utility

The "extension of utility" is the underlying rationale for adaptable product design (Gu et al. 2004). The purpose of any product is to perform the intended functions, which can be called "normal operational mode". This is also known as the "utility" of the product (Gu et al. 2004). The "extension of utility" means that the aim for the design of an adaptable product is to extend the utility of the product into operational modes for which the product, if not made adaptable, would not be useful. However, when the requirements change such as new functions are needed or more advanced technologies are developed, the current operational mode of a product may no longer satisfy these new requirements. This extended utility enhances user's satisfaction, reduces the need for frequent purchases, and provides better long-term value for the product throughout its lifecycle. While acquiring a new product is often an option when operational modes change, the adaptable product design approach promotes modifying the existing product to meet the new requirements. Adaptable products, when well-designed, should be relatively easy for users (or contractors requested by the users) to modify and the adaptation process should be cost-effective for the user. By extending the utility and service life of the product, and the ability to replace multiple products, adaptable products offer users significant cost savings. Instead of following the traditional design

approach that focuses on restoring a product's functionality to a predefined level through maintenance and repair, as shown in Figure 2.2(a), adaptable product design allows for improvements of product functionality through modifications, such as upgrading, as shown in Figure 2.2(b).



(a). Traditional design **(b).** Adaptable product design

Figure 2.2. Traditional design and adaptable product design considering product functionality (Gu et al. 2009)

Environmental benefits

Reducing the environmental impact of a product throughout its lifecycle has become a key objective in design and manufacturing. Traditional product lifecycles, which start from raw material extraction to retirement, often result in significant resource consumption and waste generation. To mitigate these effects, several strategies, such as recycling (Li 2019; Karim and Nakade 2022), remanufacturing (Diallo et al. 2017; Nasr 2024), and product adaptation (Gu et al. 2009), have been developed to minimize environmental impact, as shown in Figure 2.3. Recycling returns the materials from the retired product stage to earlier stages such as material processing, while remanufacturing redirects the components of the retired product into later stages of the production chain, potentially offering greater benefits than recycling. Product adaptation occurs during the operation phase, allowing the product to be modified, such as being upgraded, to extend its lifespan. Compared with recycling and remanufacturing, the design of adaptable products considering product adaptability can further reduce the waste created in the remanufacturing and recycling processes by only modifying a small number of the existing components/modules of a product to extend its lifespan to satisfy the new required functions.

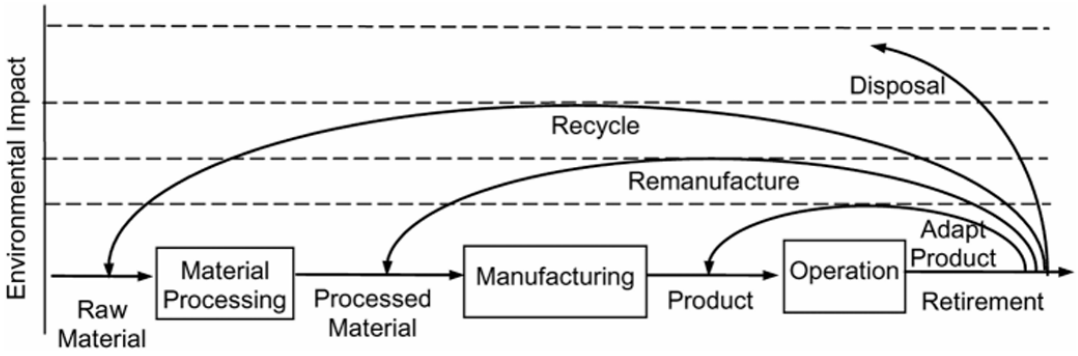


Figure 2.3. Various methods to reduce the environmental impact (Gu et al. 2009)

Economic benefits

The adaptable product design offers a wide range of economic benefits across the entire product lifecycle. When adaptable product design method is used to create new designs, existing designs are reused to save time and effort in the new product development process. Instead of discarding or recycling a product when its functions cannot be restored through maintenance (De Campos and Simon 2019; De Jonge and Scarf 2020) and repair (Mezafack et al. 2022; Van Oudheusden et al. 2023) work or when they no longer meet the new requirements, the product can be modified by changing some of its components/modules to achieve the desired new functions. Therefore, the process of adapting an existing product, compared with the creation of a new product from scratch, can result in savings in product development lead time and costs for the producer, thus making the product more competitive in the marketplace.

2.2. Methodology for the Design of Adaptable Products

Development of advanced design theory and methodology is widely recognized as an effective approach to improve product competitiveness in the marketplace (Tomiyama et al. 2009). In the following sections, Section 2.2.1 presents a literature review on the commonly used design methodologies, such as modular design, product platform/family design, mass customization product design, reconfigurable product design, and robust design, as well as various Design for X (DfX) approaches that aim to improve the competitiveness of the products in the marketplace. Section 2.2.2 then addresses the core issues in the adaptable product design approach, including modelling, evaluation, and optimization.

2.2.1. Common design methodologies

Prior to the introduction of adaptable product design concept, many design methods, including modular design, product platform/family design, mass customization product design, reconfigurable product design, robust design, and Design for X (DfX), have been developed for design of mechanical products to better satisfy the customer requirements.

Modular design

Modular design approach has been widely used for providing product variety and reducing production costs. In modular design, some components in a product are grouped into relatively independent modules such that these modules can be easily assembled in manufacturing and disassembled in maintenance non-destructively (Bonvoisin et al. 2016; Ma and Kremer 2016). The different components are usually grouped into modules based on their similarities in functions, technologies, structures, and/or manufacturing processes (Fixson 2007; Salonitis 2014). Since the modules are relatively independent, they can be designed and manufactured separately. In addition, manufacturing cost can be reduced, and product variety can be increased by designing standard modules to be used in different products. Modular design serves as basis for adaptable product design. Generally, the modular design can be used for creating adaptable products through developing changeable modules based on the changeable requirements. Martinez and Xue (2018) introduced a new modular design approach considering the whole product utilization spans to identify modules for design of adaptable products. In this work, the product components with similar lifecycle properties such as operation phases and lifespans were grouped into modules using a fuzzy pattern clustering method. Although products developed using adaptable design have the modular architectures, modular products are not necessarily adaptable products that can be changed in the operation stages to satisfy the changed requirements.

Product platform/family design

The products sharing the same platform usually form a family of products. Product platform/family design method is an extension of the modular design method through the use of the platform in all the designs of a product family (Jiao et al. 2007; Simpson et al. 2014; Gauss et al. 2021). In the design of adaptable products, platform design approach can be used to achieve the different functions of the products in a product family. When certain functions are required,

the modules with these functions are then attached to the platform. Cheng et al. (2017a) introduced a novel design method to identify an adaptable product platform for a family of heavy-duty gantry milling machines based on sensitivity design structure matrix. In this work, the customer requirements were first classified into different groups based on K-means clustering method. Sensitivity design structure matrix was then employed to separate non-adaptable parameters in non-adaptable platform modules and adaptable parameters in adaptable platform modules. Although product platform and family design can better satisfy the customer needs with a variety of products, changes in functional requirements of the purchased products are usually not considered in the design process.

Mass customization product design

Mass customization product design is an approach to produce customized products based on the requirements of individual customers with near mass production efficiency (Fogliatto et al. 2012; Smith et al. 2013; Hou et al. 2022). The computer-based design systems as well as production planning systems are usually required for mass customization (Gu et al. 2009). An example of a mass customized product is a personal computer that allows different customers to select different modules based on their needs. Since mass customized products are usually modelled by exchangeable modules, mass customization product design can be employed in the design of adaptable product approach. Although products created using mass customized product design method can satisfy individual customer's needs at product purchasing stage, these products may not be adaptable in the operation stages.

Reconfigurable product design

Reconfigurable products, such as reconfigurable machines, are designed to replace multiple products with single ones (Landers et al. 2001; Katz 2007; Gadalla and Xue 2017). Reconfigurable products can be changed in the operation stages to satisfy different functional requirements. In research on design of reconfigurable mechanical products and systems, Kalyanasundaram and Lewis (2014) introduced a method to combine functional structures of the existing products to obtain the overall functional structure of the reconfigurable product to deliver multiple functions. Gadalla and Xue (2018) presented an approach to identify the optimal configurations and reconfiguration processes for design of reconfigurable machine tools. This approach was further

improved by considering the dependency relations among descriptions of design/process candidates and evaluation criteria (Gadalla and Xue 2020). In reconfigurable product design, although the reconfigurable products can be changed in the operation stages to satisfy different functional requirements, new functions cannot be added during operation stages.

Robust design

Products created through robust design approach can deliver the required functions even under uncertain conditions such as manufacturing process variations or operating condition variations (Arvidsson and Gremyr 2008; Hasenkamp et al. 2009; Gremyr et al. 2014). The uncontrolled variations that may affect the product's performance are described by the term "noise". A high-quality product should not be sensitive to noise factors. The robust design method was first introduced by Taguchi in the 1970s (Taguchi 1978). Robust design aims at improving the desired performance of the product while minimizing the effects of noise. For the design of an adaptable product, due to its complex architecture, multiple functional requirements, and changes of product's configurations and parameter values in operation stage, impact of uncertainties to the functional performance measures should be considered. Zhang et al. (2014b) developed a robust adaptable design approach considering changes in requirements and parameters during the product operation stage by optimization with an objective function defined by both the evaluation measures and variations of evaluation measures due to noise. This robust design method was further extended by considering changes in product configurations (Zhang et al. 2014a) and the design of open architecture products (Zhang et al. 2015). Deabae and Xue (2025) also introduced a new robust adaptable product design method to identify the optimal design including the product configurations and parameter values considering uncertainties in both product configurations and product parameters.

Design for X (DfX)

Design for X is an approach to incorporate one downstream product lifecycle aspect into the design phase, thereby generating a design with good evaluation measure to that aspect (Holt and Barnes 2010; Chiu and Kremer 2011; Sassanelli et al. 2020). Typical Xs include manufacturing, assembly/disassembly, and recycling. Design for manufacturing (DFM) and design for assembly (DFA) (Kuo et al. 2001; Battaïa et al. 2018) methods were developed from the fact that the cost of

producing a product is largely determined by its design. Failing to consider manufacture and assembly in design can result in products that are either fundamentally impossible to make, or more expensive, and hence less profitable, than they should be. The focus of these techniques is therefore to reduce the cost of product development, either by minimizing manufacture and assembly costs, or by avoiding unnecessary design iterations. Similar to DFA, design for disassembly (DFD) (Desai and Mital 2003) establishes and evaluates feasible disassembly sequences for a product. Evaluation is sometimes based on the time/cost of disassembly. The easier a product is to disassemble, the greater the chance that its parts will be reused or recycled. Design for recycling (DFR) (Yadav et al. 2018) is closely related to DFD. After all, assemblies whose parts are difficult to separate are much more difficult to recycle. Other DfX methods developed in the literature (Holt and Barnes 2010) to improve product quality, lifecycle performance, and overall design efficiency include design for quality, design for maintenance, and design for reliability.

2.2.2. Key issues in developing the adaptable product design methods

Since the introduction of the adaptable product design concept, significant efforts have been devoted to research in this area (Gu et al. 2004; Gu et al. 2009; Gu et al. 2024). Many new methods and tools have been developed to overcome the challenges primarily in design modelling, design evaluation, and design optimization.

Modelling for the design of adaptable products

Modelling of adaptable products serves as a foundation for the design of adaptable products. An adaptable product is described by its functions and solutions. Therefore, it is required to model design functions and design solutions considering product adaptability.

(1) Functional modelling

The design requirements are usually modelled by functions and sub-functions. A primary goal of adaptable product design is to extend the functionality of products. Therefore, it is required to model design functions considering product adaptability (Erden et al. 2008). In addition, function changes, such as the potential functions that may be used in the future, should be modelled. Modelling of multiple functions to replace multiple products with a single one is also required.

The major requirements for function modelling in the design of adaptable products were outlined by Gu et al. (2009) as follows:

- When a product is created using the adaptable product design approach to provide multiple functions that are usually delivered by multiple products, the modelling of multiple and/or alternative functions is needed.
- Due to the complexity of adaptable product design, modelling of functions and their associated relations at multiple levels is required.
- Modularity and independence of functions must be considered, as functions may be added, removed, or modified in the design of adaptable products.
- Function modelling should capture/describe both qualitative and quantitative requirements.

(2) Design solution modelling

The design of an adaptable product should be modelled such that the product can be easily changed to deliver the new functions. The relationships between design functions and design solutions should also be modelled to identify the multiple design candidates that can deliver the required functions for selection of the best one. A design solution is often modelled by structure of the product (Lyu et al. 2017). A structure is composed of components, assemblies, and parameters of these components and assemblies. For adaptable product design, changes of the product in operation stage should also be modelled. The major requirements for design solution modelling in the design of adaptable products were outlined by Gu et al. (2009) as follows:

- Due to the complexity of a product's structure in the design of adaptable product, modelling of design descriptions and their associated relations at multiple levels is required.
- The relationships between design functions and design solutions should be described, as design solutions are required to achieve the desired functions.
- Design solution modelling should capture/describe both qualitative and quantitative requirements.
- An approach to reduce the product adaptation effort and cost is needed, as components/modules may be added, removed, or replaced in the design of adaptable products.

- When a product is created using the adaptable product design approach to replace multiple products, some components/modules may be used in all product configurations, and others may be used in only specific configurations of the product. The design solution modelling should clearly describe which components/modules are shared across all configurations, and which are specific to certain configurations.

Evaluation for the design of adaptable products

Development of effective evaluation methods is critical to the design of adaptable products. The design of adaptable products should be evaluated through measures such as functional performance and production costs (Gu et al. 2004). Since multiple evaluation measures with different units are often considered in the design of adaptable products, methods to convert these evaluation measures into comparable evaluation indices to build an overall evaluation index should be considered.

For evaluation of an adaptable product design, product adaptability was often used to assess the capability of an existing product to be adapted to a new one to satisfy the changed requirements (Gu et al. 2004; Li et al. 2008; Fletcher et al. 2009). When specific adaptation requirements were provided, the adaptability to change the product to satisfy these new requirements was defined as specific product adaptability (Gu et al. 2004; Li et al. 2008). Specific product adaptability was calculated by comparing relative efforts for adaptation of an existing product to the efforts required for creating a new product (Gu et al. 2004). Li et al. (2008) extended this specific product adaptability evaluation method by considering three types of product adaptation tasks: extendibility of functions, upgradeability of modules, and customizability of components. Adaptability without considering specific adaptation requirements was called general product adaptability. Fletcher et al. (2009) developed a method to measure the general product adaptability by comparing the current product architecture with the ideal (segregated) product architecture. Other measures, such as essential adaptability and behavioral adaptability (Cheng et al. 2011), product upgradability (Ma et al. 2024), and openness (Chen et al. 2018) as well as the traditional measures of performance and cost, have also been considered for adaptable product design.

Optimization for the design of adaptable products

Adaptable products are designed to satisfy different requirements of customers using fixed components/modules and changeable components/modules to form different configurations quickly. Finding the best configuration from all feasible configurations is a crucial aspect that needs to be considered in adaptable product design. When multiple design configuration candidates are created, the one with the best evaluation measure is selected for production. For the design of adaptable products, various configurations should be designed in a way such that changing from one configuration to others requires the minimum effort.

Optimization plays an important role to achieve the optimal adaptable product design solution from all feasible design solutions. Typical optimization process requires the following steps (Nocedal and Wright 2006):

- Identification of the objective function, variables and constraints
- Construction of an appropriate model to represent the product or system. If the model is overly simplified, it will not give useful insights into the practical problem. If the model is too complex, it may be difficult to solve
- Identification of an optimization algorithm to find the solution, usually with the help of a computer

Optimization tools can be used to achieve the optimal designs of adaptable products. Typical tools include:

- Constrained optimization tools based on numerical search (Nocedal and Wright 2006)
- Multi-objective optimization tools considering evaluation measures in different lifecycle aspects (Wang et al. 2011; Gunantara 2018)
- Multi-level optimization tools for identification of both the optimal configuration and the optimal parameters (Zhang et al. 2014a; Martinez and Xue 2018)
- Global optimization tools to improve optimization quality by preventing the optimal solution from falling into local optimal locations (Grossmann 2013)

2.3. Modelling, Evaluation, and Optimization for the Design of Adaptable Products

This section presents a review on the different methods of modelling, evaluation, and optimization for the design of adaptable products.

2.3.1. Modelling methods for the design of adaptable products

Since a major objective of developing an adaptable product is to extend the product's functionality, modelling of design functions has been extensively studied (Erden et al. 2008). Similarly, the research on design representation has been extensively carried out with the advances of CAD and lifecycle engineering design (Lyu et al. 2017; Baxter 2018). The major methods that can be used for modelling of functions and/or design solutions for adaptable product design include tree-based, network-based, and AND-OR tree-based modelling techniques. The design of an adaptable product should be modelled such that the product can be easily changed to deliver different functions. A design solution, modelled by a structure of the product, is composed of components, assemblies, and parameters of these components and assemblies.

In adaptable product design, various schemes, such as a simple tree, a network, an AND-OR tree, and artifacts and attributes, as shown in Figure 2.4, can be used for function modelling and/or design modelling (Gu et al. 2009). The major methods that can be used for modelling of design functions and/or design solutions in the adaptable product design are summarized as follows.

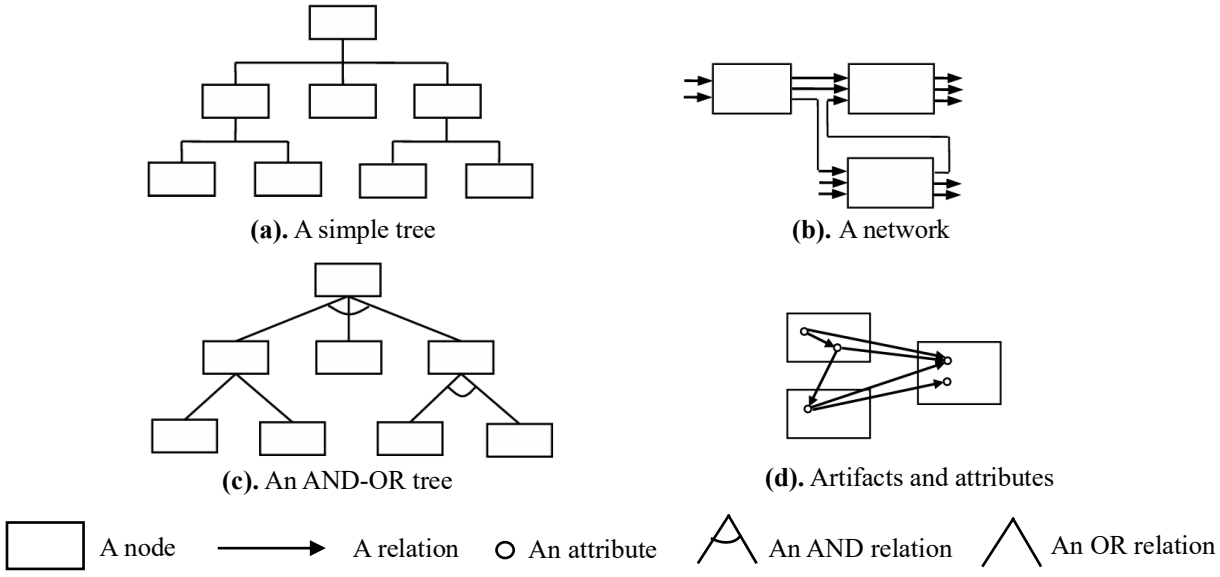


Figure 2.4. Various design function/solution modelling methods (Gu et al. 2009)

Tree-based design function/solution modelling

In a simple tree, design functions/solutions are modelled at multiple levels, as shown in Figure 2.4(a). For functional modelling, a function can be represented by a node. A complex function is decomposed into sub-functions. The root node of a simple tree represents the overall function. Solutions to the sub-functions are identified and then used to satisfy the overall function. Similarly, for design solution modelling, a complex product is decomposed into sub-systems. In a CAD system, such as SolidWorks, a product is modelled by a tree with leaf nodes representing parts and other nodes representing assemblies.

In the design of adaptable products, Gu et al. (2004) and Hashemian (2005) classified functions into physical functions and non-physical functions. The functions were modelled in a hierarchical data structure representing design rationales. This hierarchical function modelling scheme was called the rational functional structure of the design, where hierarchical functions were mapped to hierarchical physical structures in order to model the design. In this structure, functions were relatively independent, and the product could be modified easily to deliver different functions. In the work by Fletcher et al. (2009), a hierarchical data structure was also used to model a product. The same hierarchical data structure was used to describe both the physical and functional parts. Since each element of the product usually provides a certain function, this hierarchical data structure of product functions was then mapped to a hierarchical data structure of product parts.

Network-based functional modelling

The network scheme is usually used for function modelling in the design of adaptable products. In this method, relations among functions form a network, as shown in Figure 2.4(b). The relations can be modelled by different types of flows, including materials, energy, and information flows (Pahl et al. 2007).

In the design of adaptable products, a product defined by a network-based structural model can be difficult for product adaptation. Therefore, Fletcher et al. (2009) changed the design from the network-based structure to tree-based structure, called segregated structure, which played an important role in the design of adaptable products. Fletcher et al. (2009) studied general product adaptability considering different structures of the considered product. They found that the design

modelled by a segregated structure (i.e., tree structure) provided better product adaptability than the design modelled by a full structure (i.e., network structure).

AND-OR tree-based design functions/solution modelling

For modelling of an adaptable product design, the AND-OR tree introduced by Xue (1997) was effective for modelling design functions, and alternative product configurations to satisfy the same required design functions, as shown in Figure 2.4(c). In an AND-OR tree, AND and OR relations among sub-nodes are used to define the composition and alternative functions/solutions of design descriptions. In this scheme, if all sub-nodes have to be satisfied to achieve a super-node, these sub-nodes are associated with an AND relation. If only one sub-node needs to be satisfied to achieve a super-node, these sub-nodes are associated with an OR relation. Each node in the AND-OR tree is associated with design parameters. Tree-based search (Russell and Norvig 2002) can be used to generate design candidates.

In the design of adaptable products, the AND-OR tree was often used to model the generic product design considering different product configurations and their parameters to satisfy the same design requirements (Zhang et al. 2014a; Martinez and Xue 2018). The AND-OR tree can be used to model the different alternative design candidates to identify the optimal one. In the work by Zhang et al. (2014a), a hybrid AND-OR tree was developed by introducing an OR relation in operation (OR-O), in addition to the regular AND and OR relations. When different components, assemblies and modules of the adaptable product needed to satisfy the different requirements in different operation phases, the relevant design nodes were associated with an OR-A relation. Martinez and Xue (2018) utilized the hybrid AND-OR tree to model all feasible design solutions considering different configurations and their parameters for the design of adaptable products considering the whole product utilization spans. Similarly, Gadalla and Xue (2018) used the hybrid AND-OR tree to model the different product design candidates and reconfiguration process candidates, and the parameters of design and process of reconfigurable machine tools.

Qualitative information and quantitative information in design solution modelling

This scheme was developed by Xue and Yang (2004) to model both qualitative information and quantitative information in design solution using artifacts and attributes. In this scheme, design nodes were modelled by artifacts, where each artifact was described by attributes. Each artifact

represented either a component or an assembly. For modelling of quantitative information, an attribute was associated with a value. The quantitative relations among attributes were modelled by numerical functions. When the value of one attribute was modified, this change was propagated to the other relevant attributes through the quantitative relations.

2.3.2. Evaluation methods for the design of adaptable products

Design for adaptable products should be evaluated through measures in design such as functional performance and production costs. When multiple design candidates are created, the one with the best evaluation measure is selected for production. Product adaptability was often used to evaluate the design solutions for the optimal design of adaptable products. When requirements for product adaptation are specific or can be predicted at the design stage, the product adaptability is called "specific product adaptability" (Gu et al. 2004; Li et al. 2008). When requirements for product adaptation are unknown or unpredictable at the design stage, the product adaptability is called "general product adaptability" (Fletcher et al. 2009). Product lifecycle evaluation measures, such as manufacturability (Shukor and Axinte 2009) and serviceability (Gobbo and Borsato 2021), can also be considered for the design of adaptable products.

Evaluation of specific product adaptability with specific adaptation requirements

In the past, research on the evaluation of product adaptability primarily focused on the development of various measures to evaluate specific product adaptability. Gu et al. (2004) defined a measure of specific product adaptability by comparing the cost of an adaptation task to modify an existing product and the cost of creating a new product to satisfy a new requirement. Li et al. (2008) extended this specific product adaptability by considering different types of product adaptation tasks: extendibility of functions, upgradeability of modules, and customizability of components. Uckun et al. (2014) introduced a method to evaluate product adaptability based on product architecture characteristics, including modularity, hierarchy, interfaces, and performance sensitivity. The specific adaptability was defined as a weighted summation of these architectural characteristics. Engel et al. (2017) introduced a measure called the architecture adaptability value (AAV) by considering both the benefits of more architecture options and the costs of interfaces. In this work, the option value of each component was defined as the difference between the component's present cost and the expected benefit of changing it in the future. Cheng et al. (2017b)

developed a method to measure the adaptability of an adaptable product platform based on the information content in the axiomatic design method. In their research, four aspects of adaptability, namely reusability, customizability, interface flexibility, and upgradeability, were considered. The information content was calculated by the probability of success of a design in meeting the specified functional requirement. Sun et al. (2024) developed a method to evaluate the adaptability of a design candidate by calculating the extra design effort for satisfying the design requirements, which was the difference in information content between the design candidate and design requirements based on the information entropy theory.

Since many existing design methods, including modular design, product platform/family design, mass customization product design, and reconfigurable product design, can also be used for achieving some of the goals in the design of adaptable products, evaluation measures developed in these methods can also be considered in adaptable product design. The popular modular design method aims at clustering components into modules, such that the same standard modules can be used for building different products to reduce efforts in manufacturing, maintenance, and repair (Bonvoisin et al. 2016). Various modularity measures were introduced to evaluate the degrees to which products' components can be separated and recombined (Gershenson et al. 2004; Fixson 2007; Bonvoisin et al. 2016). Product platform/family design method is an extension of the modular design method through the use of a shared common module, called a platform, in all the designs of a product family (Jose and Tollenaere 2005; Simpson et al. 2006; Jiao et al. 2007; Ripperda and Krause 2017; Vogt et al. 2024). Commonality was introduced as a measure to evaluate the degree of component/module sharing in product platform/family design (Thevenot and Simpson 2006; Fixson 2007; Gauss et al. 2021). Mass customization product design is an approach to produce customized products based on the requirements of individual customers with near mass production efficiency (Hong et al. 2008; Fogliatto et al. 2012; Smith et al. 2013; Hou et al. 2022). Customizability of components was developed as a measure to evaluate the ease of product customization based on the requirements and preferences of individual customers (Jiao and Tseng 2004). Reconfigurable products, such as reconfigurable machines, are designed to replace multiple products with single ones (Landers et al. 2001; Setchi and Lagos 2008; Gadalla and Xue 2017). Reconfigurability measures were developed to evaluate the ability to repeatedly change and/or rearrange the components of a system in a cost-effective way, to meet different requirements of customers (Maganha et al. 2018; Napoleone et al. 2018). Other measures

considering product changes, including product upgradeability (Xing and Abhary 2010; Ma et al. 2024), changeability (Ross et al. 2008; Varl et al. 2022), and degree of similarity between different adaptable functions (Yang and Deng 2017), can also be used to evaluate the product adaptability.

While modularity, commonality, customizability, and reconfigurability in the popular design methods have been widely used to evaluate product flexibility and variety to reduce costs and to meet customer preferences, the objectives and activities of these methods are different from those for adaptable product design, as summarized in Table 2.1. The evaluations of product adaptabilities using these methods were typically achieved from the available information, such as specific design functions, selected components and their relations, and manufacturing constraints. The products manufactured based on the modular design, product platform/family design, and mass customization product design methods are usually not adaptable in the operation stages. Although the reconfigurable products can be changed in the operation stages to satisfy different functional requirements, these requirements must be provided at the design stage. Adaptations of products in the operation stages to satisfy new functions were not considered in these popular design methods. These methods exhibit inherent limitations in addressing unpredictable or unforeseen adaptation requirements during the product's operation stage.

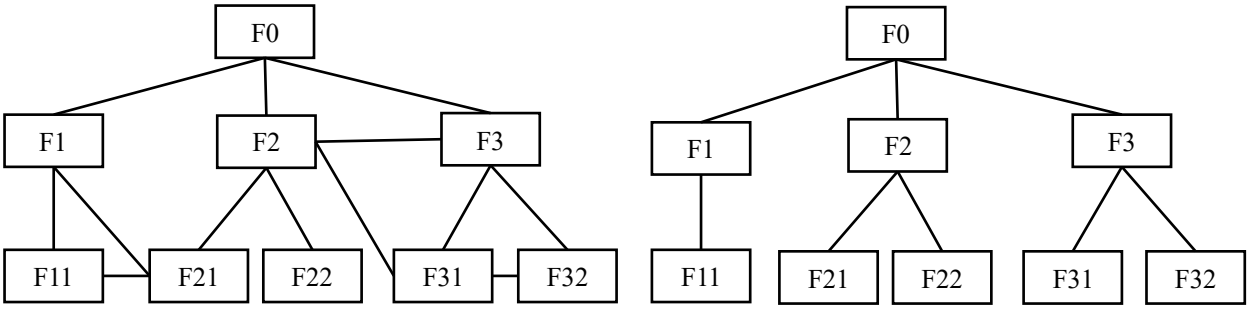
Table 2.1. Comparison between adaptable product design method and other design methods

Design Method	Modules are often used	Different product configurations are created from the same model	User is involved in design or operation	Product can be changed in operation stage	New function can be added in operation stage
Modular Design	Yes	No	No	No	No
Product Platform / Family Design	Yes	Yes	No	No	No
Mass Customization Product Design	Yes	Yes	Yes	No	No
Reconfigurable Product Design	Yes	Yes	Yes	Yes	No
Adaptable Product Design	Yes	Yes	Yes	Yes	Yes

Evaluation of general product adaptability without specific adaptation requirements

In real-world applications, products often encounter unanticipated changes in operating environment, user demands, regulatory requirements, or technological advancements that arise during their operation stages. In the traditional design evaluation measures, such unpredictable adaptation requirements were not considered, thus limiting the effectiveness of these measures in ensuring long-term product adaptability.

Compared with the evaluation of the specific product adaptability when potential changes in requirements are provided at the design stage, evaluation of the general product adaptability faces challenges due to the lack of predictable requirement changes. Fletcher et al. (2009) developed a method to evaluate the general product adaptability by comparing the actual architecture of the product with the ideal segregated architecture of this product, as shown in Figure 2.5. In their work, a product was modelled by a hierarchical data structure. When only parent nodes and their child nodes were associated by relations, the design was modelled by a tree, and the architecture was called "segregated product architecture." When other nodes were also associated by relations, the design was modelled by a graph, and the architecture was called "full product architecture". The segregated product architecture was ideal for adaptable product design, since modification to a node in this architecture didn't impose influence on other nodes at the same level. In addition, various aspects of the relations (i.e., interface relations and interaction relations, and functional relations and physical relations) and the importance of the nodes (i.e., cost percentages of the components for the product) for these relations were also considered to define the general product adaptability.



(a). A full product architecture **(b).** A segregated product architecture

Figure 2.5. Full product architecture and segregated product architecture (modified from Fletcher et al. (2009))

2.3.3. Optimization methods for the design of adaptable products

Among various research aspects for adaptable product design, identification of the optimal design configurations and parameters has been recognized as a key to achieve the design solution based on changing requirements. Optimization plays an important role to achieve the optimal design solution from all feasible design solutions.

Multi-objective optimization

Since the design of adaptable product is evaluated by product adaptability and other evaluation measures in different lifecycle phases, such as cost measures, time measures, and performance measures, identification of the optimal design solution is a typical multi-objective optimization problem. A multi-objective optimization problem is defined by (Branke 2008; Gunantara 2018; Chen 2023):

$$\min_{w.r.t.\ \boldsymbol{X}} \left(F_1(\boldsymbol{X}), F_2(\boldsymbol{X}), \cdots, F_m(\boldsymbol{X})\right) \tag{2.1}$$

where $F_1(\boldsymbol{X})$, $F_2(\boldsymbol{X})$, …, $F_m(\boldsymbol{X})$ are m objective functions to be minimized, and $\boldsymbol{X}$ represents the vector of parameter variables.

A simple way to solve a multi-objective optimization problem is to convert these different objective functions, usually in different units and scales, into comparable unitless quantities. Several methods have been developed to convert the different design evaluation measures with different units into comparable unitless values (Xue et al. 1996; Yang et al. 2006). Xue et al. (1996) introduced a method to combine different objective functions together by comparing their improvement from a selected basic design as follows.

$$\min_{w.r.t.\ \boldsymbol{X}} \sum_{i=1}^{m} \frac{F_i(\boldsymbol{X}) - F_i(\boldsymbol{X}_0)}{F_i(\boldsymbol{X}_0)} \tag{2.2}$$

where $\boldsymbol{X}_0$ was the selected basic design. In this approach, the results of the optimization were different when different basic designs were selected. Yang et al. (2006) developed a more general approach to solve the multi-objective design optimization problems. In their approach, the various objective functions modelled by various evaluation measures were converted into evaluation indices using nonlinear relations between evaluation measures and evaluation indices, as follows.

$$I_i(\boldsymbol{X}) = I_i[F_i(\boldsymbol{X})],\ i = 1,2,\dots,m \tag{2.3}$$

where $I_i(\boldsymbol{X})$ was described by a number between 0 and 1 without unit representing how good the design was considering the selected design evaluation measure. The relation between an evaluation measure, $F_i(\boldsymbol{X})$, and its evaluation index, $I_i(\boldsymbol{X})$, was usually a non-linear relation. The non-linear relation was defined by pairs of discrete points obtained by experts and/or customers' satisfaction rating for the given evaluation measures. In optimization, however, a continuous function between an evaluation measure and its evaluation index is usually required. The least-squares curve-fitting method (Hoffman and Frankel 2018) was usually used to identify this continuous function. The non-linear relation between an evaluation measure and its evaluation index was defined by a cubic polynomial, as follows.

$$I_i(\boldsymbol{X}) = a_{0,i} + a_{1,i}F_i(\boldsymbol{X}) + a_{2,i}F_i^2(\boldsymbol{X}) + a_{3,i}F_i^3(\boldsymbol{X}), \quad i = 1,2,\dots,m \tag{2.4}$$

where, $a_{0,i}$, $a_{1,i}$, $a_{2,i}$, and $a_{3,i}$ are the four coefficients of the cubic polynomial function.

The final objective function was then defined by:

$$\underset{\text{w.r.t. } \boldsymbol{X}}{max}\, I(\boldsymbol{X}) = W_1 I_1(\boldsymbol{X}) + W_2 I_2(\boldsymbol{X}) + \cdots + W_m I_m(\boldsymbol{X}) \tag{2.5}$$

where W_1, W_2..., W_m were m weighting factors between 0 and 1 representing the relative importance for each of these evaluation indices. These individual weighting factors could simply be selected/assigned based on the experience and judgment of experts and/or customers' preferences. Other methods, such as the pair-wise comparison method (Saaty 1980; Ishizaka and Labib 2011), have also been developed to identify the weighting factors of different evaluation measures.

Multi-level optimization

In the design of adaptable products, a product design is often modelled by its configurations and parameters. Therefore, optimization to select the best design configuration and the best design parameter values must be considered when many feasible design configurations and parameter values can be selected.

The multi-level optimization considering product configurations and their associated parameters was formulated to identify the best design configuration candidate and its parameter values (Xue 1997). In the design of adaptable products, optimization was often conducted at two levels: configuration level and parameter level (Xue et al. 2012; Zhang et al. 2014a; Martinez and Xue 2018). The two-level optimization was conducted in a loop. In this loop, first a feasible design configuration candidate was generated, and parameter optimization for this design configuration candidate was then carried out. In this optimization model, the optimal design parameter values for the *i-th* design configuration solution candidate were achieved through parameter optimization.

Find: parameters $\boldsymbol{X_i}$

Optimize: $I^{(i)}$

Subject to: $\boldsymbol{X}_i^{(L)} \leq \boldsymbol{X}_i \leq \boldsymbol{X}_i^{(U)}$,

$h_j(\boldsymbol{X}_i) = 0,\ j = 1,2, \ldots$

$g_j(\boldsymbol{X}_i) \leq 0,\ j = 1,2, \ldots$ (2.6)

where $I^{(i)}$ was the selected evaluation index, $\boldsymbol{X}_i^{(L)}$and $\boldsymbol{X}_i^{(U)}$ were the lower boundaries and upper boundaries of the parameter vector $\boldsymbol{X_i}$, respectively, and $h_j(\boldsymbol{X}_i)$ and $g_j(\boldsymbol{X}_i)$ were equality constraints and inequality constraints, respectively. Among all the p feasible product design configuration solution candidates, the optimal design solution was obtained through configuration optimization.

Find: the i-th design configuration candidate

Maximize: $I = I^{(i)}$

Subject to: $1 \leq i \leq p$ (2.7)

When the design configuration candidates and their associated parameters were modelled using an AND-OR tree, the optimal design configuration candidate and the associated parameter value were obtained based on the following rules.

- A possible design configuration candidate was created from the AND-OR tree using tree-based search.

- The optimal parameter values of a design configuration candidate were obtained through parameter optimization using numerical search.
- Different design configuration candidates were evaluated by their best evaluation indices corresponding to the optimal parameter values in order to identify the best design configuration candidate.

In the design of adaptable products, an optimal adaptable product design approach was developed by Xue et al. (2012) to identify the best product design candidate. In this approach, the changes of design requirements, configurations, and parameters in the whole product lifecycle were considered. Zhang et al. (2014b) developed a robust adaptable design approach considering changes in requirements and parameters during the product operation stage by optimization with an objective function defined by both the evaluation measures and variations of evaluation measures due to noise. This robust design method was further extended by considering changes in product configurations (Zhang et al. 2014a) and the design of open architecture products (Zhang et al. 2015). Martinez and Xue (2018) employed a multi-level optimization model to identify the best design configuration solution candidate and its design parameter values considering the whole product utilization span.

Optimization to identify the optimal product configuration was also considered in other engineering product design methods. Levandowski et al. (2015) developed an engineering-to-order configuration design method through optimization considering the influence of customers with different requirements. Sabioni et al. (2021) developed a nonlinear integer programming model to optimize the configurations of mass customized products and reconfigurable manufacturing systems. Weng et al. (2021) introduced a model to evaluate complexity of design and redesign of products for development of adaptable function mechanical products. The design modules were evaluated, and the optimal one was obtained to be used for further modular design.

When the number of possible design configuration candidates was large, genetic programming (Rao 2009) was often employed for optimization. Genetic programming is an evolutionary method to solve an optimization problem when solutions to the optimization problem can be modelled by tree data structures (Hong et al. 2008). In genetic programming, individuals were used to describe the multiple design solutions in the population of a generation. Reproduction, crossover and mutation were the three operations used to evolve individuals from a generation to the next one

with a better average evaluation measure (Li et al. 2007; Hong et al. 2008; Zhang et al. 2014a). Li et al. (2007) presented an evolutionary method dealing with interwoven structural optimization of adaptive platform product customization. In this method, genetic programming was employed to handle the structural optimization. In the work by Zhang et al. (2014a), the optimization to identify the optimal product design configuration was conducted based on genetic programming. Hong et al. (2008) identified the optimal product configuration and its parameters with the maximum overall customer satisfaction index in one-of-a-kind production by genetic programming and constrained optimization.

Chapter 3. An Efficient Optimization Approach to Identify the Adapted Product Design Configuration and the Product Adaptation Process with Initial Evaluation of Information Quality in the Branches of an AND-OR Tree Based on Information Entropy

3.1. Introduction

Product adaptation is carried out by modifying a product, such as upgrading its modules, to satisfy new customer requirements. Compared with the creation of a new product from scratch, the process to adapt an existing product (i.e., manufactured product) to a new one can result in savings in costs.

As explained in Chapter 1, the scopes of adaptable product design are classified into the following two categories.

- *Design for adaptation of existing products*

  This type of design focuses on obtaining the design solution for adaptation of an existing product (i.e., manufactured product). In this type of design, multiple adapted product design solutions are usually created and evaluated for selection of the optimal one.

- *Design of new adaptable products*

  Adaptation of existing products can sometimes be difficult since product adaptation was not considered during the design stages. To solve this problem, the approach to design new adaptable products that can be easily changed during their operation stages should be considered. In this type of design, multiple design solutions of the original product configuration before adaptation are also considered in addition to the multiple design solutions of the adapted product configuration for each of the original product design configurations, for selection of the optimal original product design configuration and adapted product design configuration.

In this chapter, only the design for adaptation of existing products is considered. Design of new adaptable products will be discussed from Chapter 4.

From the problem statements and research objectives as explained in Chapter 1, research in this chapter focuses on the following key issues.

(1) Adaptable product design considering both design solutions and adaptation process solutions

An adaptation process is usually defined by a collection of operations and operation parameters to change a product from its original configuration to its adapted configuration. In the past, only product configurations and product parameters were considered in adaptable product design. Since the product adaptation process sometimes also requires significant efforts, identification of both the optimal product design (i.e., design configuration and design parameters) and the optimal adaptation process (i.e., a collection of operations and operation parameters) from all possible solutions must be considered.

(2) Improvement of optimization efficiency considering both design solutions and adaptation process solutions

In this work, the generic design considering multiple solutions of the adapted product design and the product adaptation process is modelled by an AND-OR tree with design and process nodes. When both the adapted product design candidates and the adaptation process candidates are considered in the optimization process to identify the best solution, the optimization search space may increase significantly, causing challenges to obtain the optimal solution within the limited computation time. One way to improve the optimization efficiency is to reduce the size of the solution space by pruning branches of the AND-OR tree. Since information entropy (Shannon 1948; Hayat et al. 2020) is effective to evaluate quality of information with uncertainties, it is selected in this research to evaluate the information quality in branches of the AND-OR tree, such that the branches with poor information quality are pruned to improve optimization efficiency. The method to evaluate the branches of an AND-OR tree based on information entropy has never been developed in the literature.

3.2. The Procedure for Adaptation of Existing Products

Product adaptation is accomplished through modification of the existing product to satisfy new requirements as shown in Figure 3.1.

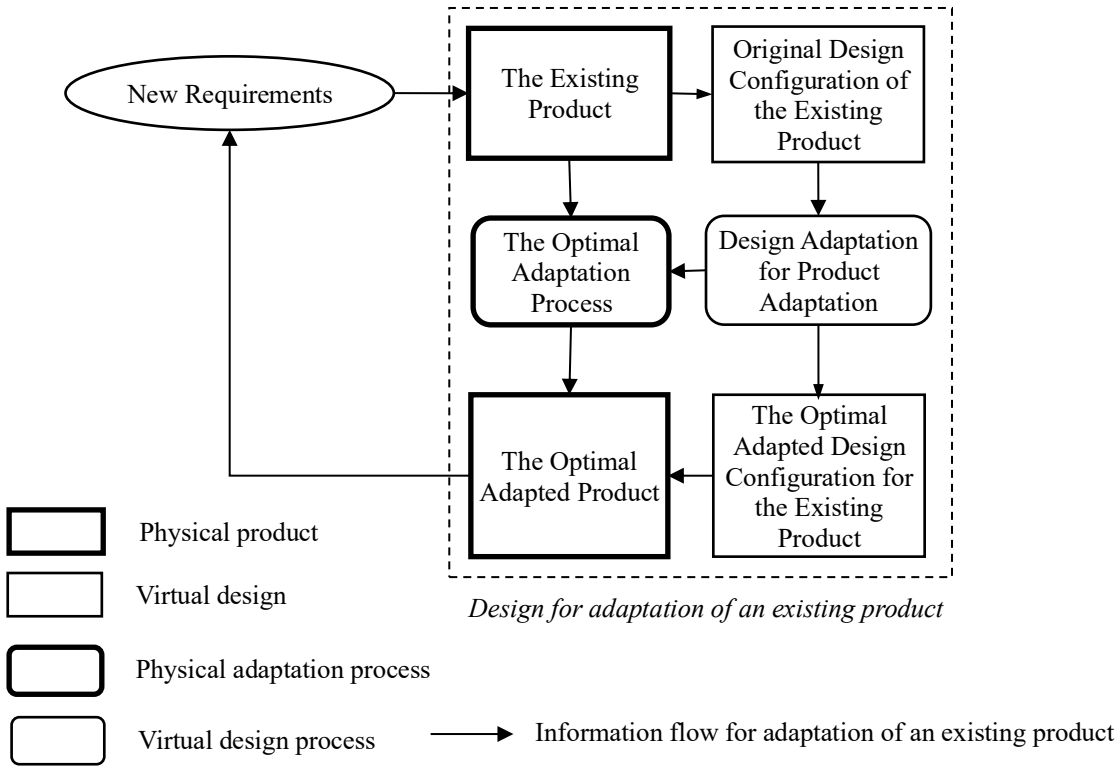


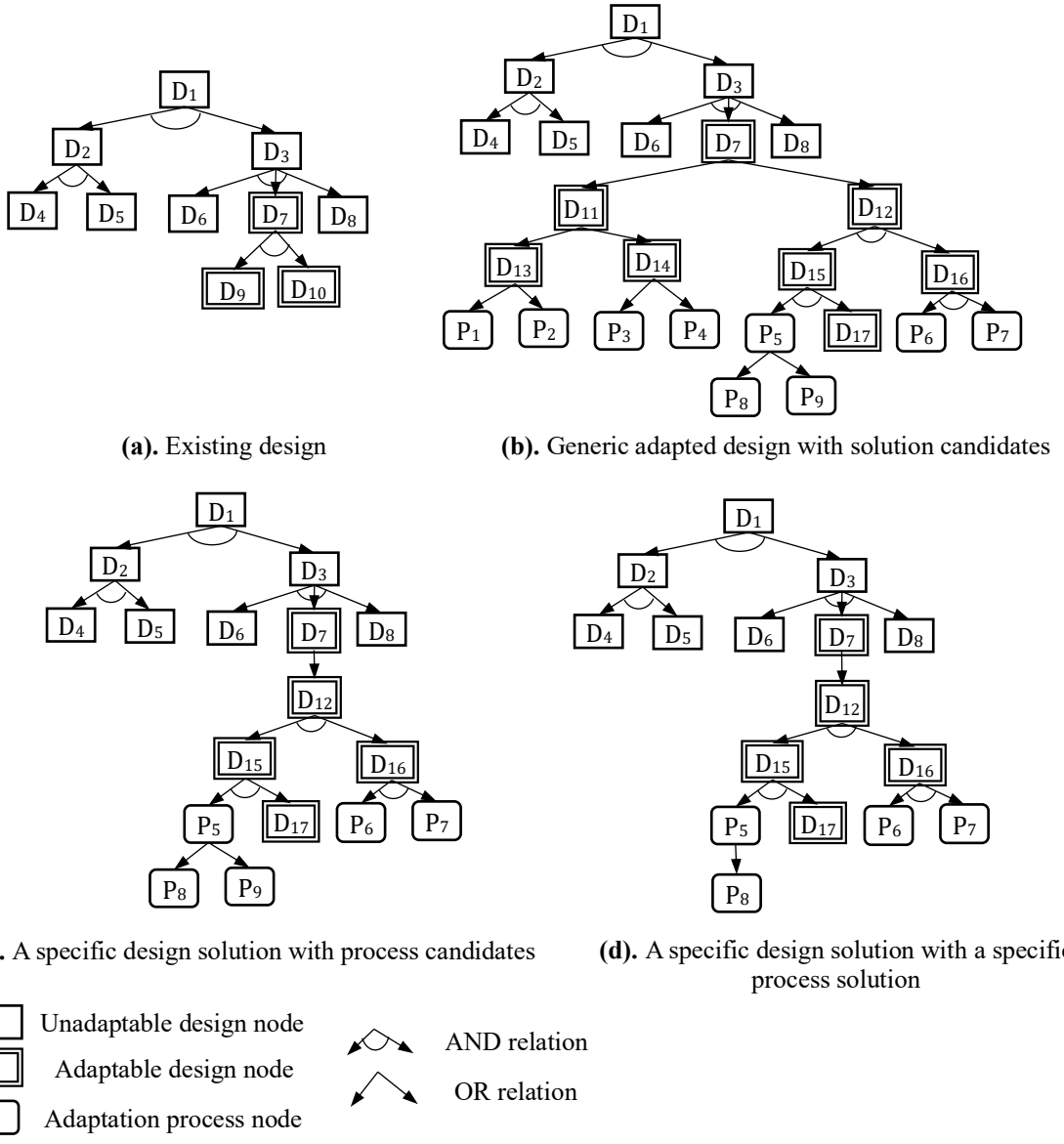
Figure 3.1. The procedure for adaptation of an existing product

The product adaptation is usually carried out through the following steps:

- Definition of new requirements
- Selection of the existing product
- Selection of the existing design corresponding to the existing product
- Creation of new design solution candidates for product adaptation through design adaptation, and creation of multiple adaptation process solution candidates for each design solution candidate
- Evaluation of the design solution candidates and the adaptation process solution candidates for identification of the best adapted design solution candidate and process solution candidate
- Change of the existing product through product adaptation process to satisfy the new requirements

3.2.1. Modelling of design and process candidates and their parameters for product adaptation

In this research, the generic solution considering the adapted product design candidates and the product adaptation process candidates is defined by an AND-OR tree, and the different design solutions and process solutions are created from the generic AND-OR tree through tree-based search as shown in Figure 3.2. The relations among sub-nodes of a super-node in an AND-OR tree are classified into AND relations and OR relations. In an AND relation, all the sub-nodes are required to support the super-node. In an OR relation, only one sub-node is required to support the super-node.



(a). Existing design

(b). Generic adapted design with solution candidates

(c). A specific design solution with process candidates

(d). A specific design solution with a specific process solution

Figure 3.2. Modelling for product adaptation

- *Modelling of the existing design*

  The design of the existing product is defined by an AND tree as shown in Figure 3.2(a). Design nodes are defined by partial design solutions such as components and assemblies. Design nodes are classified into two categories, unadaptable nodes and adaptable nodes. An unadaptable node (e.g., D4 in Figure 3.2(a)) cannot be changed for product adaptation. An adaptable node (e.g., D10 in Figure 3.2(a)) can be removed, added, or replaced by another one usually with different shape and/or function for product adaptation. Sub-nodes of a super-node are associated with an AND relation.

- *Modelling of the generic adapted design*

  The generic adapted design considering multiple solutions is defined through modification of the tree for the existing design as shown in Figure 3.2(b). The adaptable design nodes in the tree for the existing design can be changed, such as to be removed, and new design and process nodes can be added. A design node such as a component or an assembly describes a partial design solution, while a process node such as an assembly operation or a disassembly operation describes partial process solution. Sub-nodes of a super-node are associated by an AND relation or OR relation.

- *Creation of design solution candidates*

  From the generic adapted design AND-OR tree, multiple design solution candidates are created through tree-based search. A specific design solution created from the generic adapted design AND-OR tree is shown in Figure 3.2(c). When design sub-nodes are associated with an OR relation, only one of these design sub-nodes is selected to create a design solution candidate. For process sub-nodes associated with an AND relation or OR relation, all these process sub-nodes should be selected to create the design solution candidate.

- *Creation of process solution candidates*

  From each design solution candidate tree, multiple process solution candidates are created through tree-based search. A specific process solution created from a specific design solution tree is shown in Figure 3.2(d). When process sub-nodes are associated with an OR relation, only one of these process sub-nodes is selected to create a process solution candidate.

Design and process nodes are further associated with design parameters (e.g., dimensions and tolerances) and process parameters (e.g., operation time and operation temperature).

3.2.2. Evaluation of design/process candidates

A feasible solution, S_i $(i = 1, 2, \dots, p)$, for product adaptation is modelled by configuration of the adapted design, process of product adaptation, and parameters of design and process. Suppose that $\boldsymbol{X_i}$ is the vector to model all the parameters including both the design parameters and the adaptation process parameters, the design solution S_i can be evaluated by m evaluation measures:

$$F_j = f_j(\boldsymbol{X_i}), \quad i = 1, 2, \dots, p;\ j = 1, 2, \dots, m \tag{3.1}$$

where F_j represents an evaluation measure such as performance or cost, and $f_j()$ is the numerical function to obtain F_j.

The design solutions of adapted products are usually evaluated by different evaluation measures such as cost measures (e.g., total cost of configurations and adaptation processes), time measures (e.g., adaptation duration), and performance measures (e.g., reliability of the adapted product). Since multiple evaluation measures with different units are considered in this research, these evaluation measures are converted into comparable evaluation indices to build the overall evaluation index considering importance factors of these evaluation indices (Yang et al. 2006). Comparable satisfaction indices are used as the evaluation indices in this work. First, data points considering evaluation measures and their corresponding evaluation indices are obtained from customers and/or engineers. The least-squares curve fitting method is then used to obtain the numerical relations. Each evaluation index is assigned a weighting factor representing the relative importance of this index. The *j-th* evaluation measure F_j is converted into a satisfaction index I_j based on the non-linear relation between the evaluation measure and the evaluation index as follows:

$$I_j(\boldsymbol{X_i}) = g_j\big(F_j\big) = g_j\big(f_j(\boldsymbol{X_i})\big),\ i = 1, 2, \dots, p;\ j = 1, 2, \dots, m \tag{3.2}$$

where $g_j()$ is the numerical function to obtain $I_j(\boldsymbol{X_i})$, and $I_j(\boldsymbol{X_i})$ is described by a number between 0 and 1 without unit representing how good the design is considering the selected design evaluation

measure. The overall evaluation index, $I(\boldsymbol{X_i})$, considering all evaluation measures can be obtained by:

$$I(\boldsymbol{X_i}) = \frac{\sum_{j=1}^{m}\left(W_j I_j(\boldsymbol{X_i})\right)}{\sum_{j=1}^{m} W_j} \tag{3.3}$$

where W_j represents the weighting factor of the *j-th* evaluation index.

3.2.3. Identification of the optimal solution through the multi-level optimization method

In this work, the optimal solution modelled by its design configuration, adaptation process, and parameters of design and adaptation process is achieved through a two-level optimization method (Xue 1997). First, for each solution candidate with a specific design configuration and a specific adaptation process, parameter optimization is conducted to obtain the optimal values of design and process parameters through numerical search.

$$\underset{w.r.t.\,\boldsymbol{X_i}}{max}\ I(\boldsymbol{X_i}) \tag{3.4}$$

where $\boldsymbol{X_i}$ represents the vector of parameters for the *i-th* solution candidate, and $I(\boldsymbol{X_i})$ is the optimization objective function to be maximized.

Among all the solution candidates with the optimal parameter values, configuration/process optimization is carried out to achieve the optimal design configuration and its adaptation process.

$$\underset{w.r.t.\,S_i}{max}\ I(\boldsymbol{X_i^*}) \tag{3.5}$$

where $I(\boldsymbol{X_i^*})$ is the optimal evaluation index corresponding to the optimal parameter values $\boldsymbol{X_i^*}$ for the *i-th* solution candidate, and S_i is the *i-th* solution candidate.

The multi-level optimization problem can be illustrated with the following example. The design of an electric scooter is conducted by selection of components and modules such as the body stem, body deck, steering system, electric motor, battery, and braking system. Each of these components/modules can be selected from alternatives with different types and materials contributing differently to the cost and performance of the scooter. The total cost is selected as the optimization objective function, and the battery energy (watt-hour) and the motor power (watt) are

selected as the two key design variables. When the AND-OR tree is used to model the generic design of the electric scooter, multiple different configurations are created through tree-based search. For simplicity, three configurations are considered in this example. First, parameter optimization is conducted for each configuration to obtain the optimal battery energy, motor power, and the corresponding minimum total cost, as follows.

- Configuration 1 with optimal battery energy of 105 *Wh*, optimal motor power of 450 *W*, and minimum total cost of $450
- Configuration 2 with optimal battery energy of 115 *Wh*, optimal motor power of 440 *W*, and minimum total cost of $475
- Configuration 3 with optimal battery energy of 100 *Wh*, optimal motor power of 480 *W*, and minimum total cost of $480.

Among the three configurations, the one with the lowest total cost is then selected as the optimal solution through configuration optimization. In this example, Configuration 1 is selected as the optimal configuration since it achieves the lowest total cost among all the configurations.

When the number of solution candidates is not large, exhaustive method is used for configuration/process optimization. When the number of solution candidates is large, genetic programming (Koza 1993; Hong et al. 2008) is used for configuration/process optimization.

3.3. Initial Evaluation of AND-OR Tree Branches Based on Information Entropy to Improve Optimization Efficiency

3.3.1. Introduction

Although the multi-level optimization method can be used to identify the optimal design configuration, the optimal adaptation process, and the optimal values of design and process parameters, this method may not be efficient when large numbers of candidates are considered, particularly for optimization to identify both the optimal design candidate and the optimal process candidate through search with the AND-OR tree. Since information entropy (Shannon 1948; Hayat et al. 2020) is effective to evaluate quality of information in solutions with uncertainties, information entropy is selected to evaluate the information quality in branches of the AND-OR tree, such that the branches with poor information quality (i.e., are unlikely to lead to the optimal solution) are pruned to improve optimization efficiency.

Information entropy, also known as Shannon entropy, is an important measure to evaluate the uncertainty in the information (Shannon 1948; Hayat et al. 2020). Entropy was used in many different types of engineering applications. In engineering design and manufacturing, entropy was used to evaluate complexity of a design or manufacturing system (Kuzgunkaya and El-Maraghy 2006; Abad and Jin 2011; Alkan et al. 2018). The entropy of a manufacturing system was high when the system was described by a large number of states owing to the consideration of various types of resources. To manipulate the subjectivity and vagueness in design concept evaluation, Hu et al. (2015) developed an evaluation method by combining information entropy and rough number. Li et al (2020) established a customer demand information model based on rough analytic hierarchy process and information entropy. Qian et al. (2020) used entropy to measure the degree of the variation of the parameters for global optimization. Dabwan et al. (2021) used grey relational analysis coupled with entropy weights for optimization of process variables in single-point incremental forming.

3.3.2. The relations between the evaluation of information quality in branches of the generic AND-OR tree and the multi-level optimization for product adaptation

In this work, the information modelled by branches of the generic AND-OR tree is evaluated based on information entropy such that the branches without useful information leading to the optimal solution are pruned to reduce the efforts for tree-based search.

In optimization, both the optimization efficiency (i.e., the computation time or iteration number) and the optimization quality (i.e., the actually obtained maximum or minimum optimization objective function value) are used to evaluate effectiveness of the optimization methods. In fact, the optimization efficiency and the optimization quality are two perspectives of the effectiveness of the optimization method, since a better optimization quality can usually be obtained by a longer computation time. Effectiveness of a new optimization method compared with an existing one can be demonstrated by improvement of optimization efficiency with the same optimization quality or improvement of optimization quality with the same optimization computation time. Many optimization methods have been developed for improvement of optimization efficiency or quality. In this work, pruning of the AND-OR tree branches is employed to reduce the search space for improvement of the configuration/process optimization efficiency.

The relations between the evaluation of information quality in branches of the generic AND-OR tree and the multi-level optimization for identification of the optimal adapted product design, product adaptation process, and parameter values of design and process are shown in Figure 3.3.

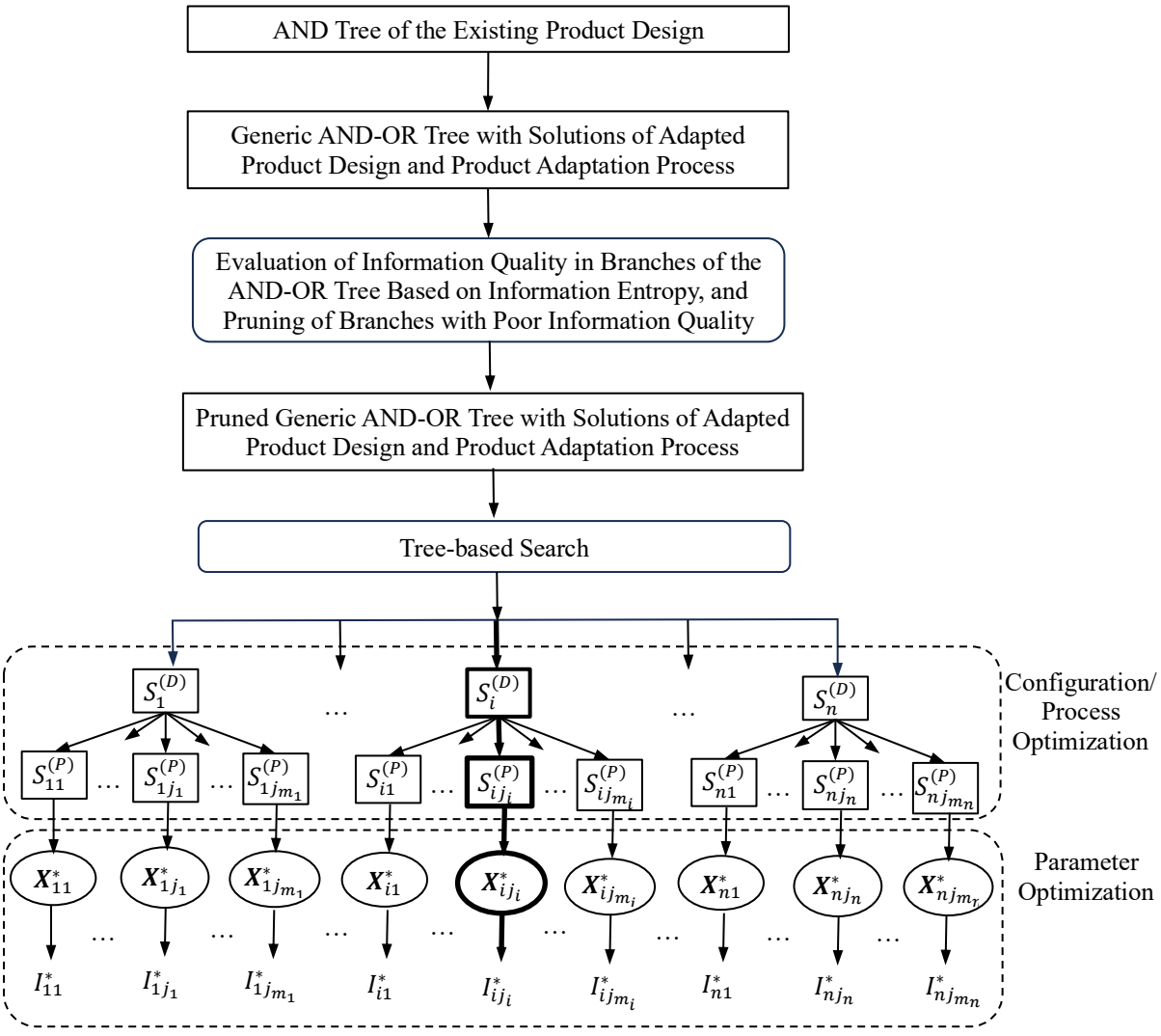


Figure 3.3. The relations between the evaluation of information quality in branches of the generic AND-OR tree and the multi-level optimization for product adaptation

First the AND tree (as shown in Figure 3.2(a)) for the existing product design is defined. Then the generic AND-OR tree (as shown in Figure 3.2(b)) considering all feasible solutions of the

adapted product design and the product adaptation process is modelled. Evaluation of information quality in branches of the AND-OR tree based on information entropy is subsequently conducted to remove the branches with poor information quality. The pruned AND-OR tree is used to create design configuration solutions $S_i^{(D)}$ (i = 1, 2, …, n) (as shown in Figure 3.2(c)), and adaptation process solutions $S_{ij_i}^{(P)}$ (j_i = 1, 2, …, j_{m_i}) (as shown in Figure 3.2(d)) from each of the design configuration solution. For a solution $S_{i_{j_i}}$ with a design configuration $S_i^{(D)}$ and an adaptation process $S_{ij_i}^{(P)}$, parameter optimization is conducted to obtain the optimal parameter values $\boldsymbol{X}_{ij_i}^*$ and the optimal evaluation index $I_{ij_i}^*$ based on Equation (3.4). Among all the design solutions, the one with the best overall evaluation index is selected as the optimal solution with its design configuration, adaptation process, and parameter values of configuration and process (as shown with the thick boxes and oval in Figure 3.3).

3.3.3. Information entropy

Information entropy is an effective tool to evaluate the amount of information considering multiple states when the probabilities of these states are not the same. A good use of information entropy should satisfy the following conditions (Shannon 1948):

- The problem should have multiple independent states.
- An event should happen as one of these states.
- Each state is associated with a probability value.
- The sum of the probabilities of all states is 1.

The entropy H satisfying the above conditions is calculated by:

$$H(X) = -\sum_{i=1}^{n} p(x_i)\, log\, p(x_i) \tag{3.6}$$

where *X* is a discrete random variable with possible outcomes x_i, and $p(x_i)$ is the probability of occurrence of the *i-th* outcome. In this work, the natural logarithm, *ln(),* with base e ≈ 2.718 is selected for the function *log()* in Equation (3.6). When all probabilities of the events are the same, the entropy *H(X)* is calculated as *ln(N)* where *N* is the number of states.

Figure 3.4 shows several trees with sub-nodes in OR relations assigned with different probabilities. Each tree has three possible outcomes. The probabilities of these outcomes are different for different trees.

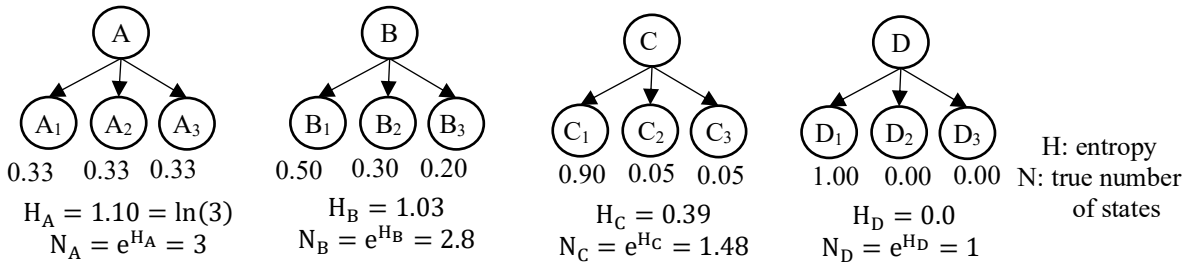


Figure 3.4. Several trees with nodes in OR relations

As shown in Figure 3.4, Tree *A* with equal probabilities of outcomes has the largest entropy, while Tree *D* with probability of one outcome as 1 and probabilities of all other outcomes as 0s has the smallest entropy of 0. It can be concluded that entropy represents the true (effective) number of states (solutions or outcomes). In other words, entropy represents the contributions of the nodes to the whole solution. Assuming the best solution is located in one of the 3 sub-nodes for each tree, when only one solution can be selected, the probability to obtain the best solution for Tree A is 33.33% and the probability to obtain the best solution for Tree D is also 33.33%. When two solutions can be selected, the probability to obtain the best solution for Tree A is 66.66%, while the probability to obtain the best solution for Tree D is still 33.33% since D_1 will be selected twice. Therefore, a tree composed of nodes with more evenly distributed probabilities has better chance to obtain the optimal result due to its larger information entropy.

The true number of solutions is calculated by:

$$N_i = e^{H_i} \tag{3.7}$$

where N_i is the true number of possible states for the *i-th* tree, and H_i is the entropy of this tree. In this work, the design/process nodes in the AND-OR tree are associated with probabilities calculated based on the different availabilities or preferences of these nodes to be selected for the solution.

3.3.4. Calculation of entropy for an AND-OR tree

For an AND-OR tree, the entropy of a super-node is calculated using the entropies of its sub-nodes.

(1) Entropy of a super-node with sub-nodes in AND relation

Figure 3.5(a) shows an AND-OR tree with two sub-nodes A and B in an AND relation. When a super-node is composed of sub-nodes with an OR relation, probabilities of these sub-nodes should be assigned. Entropies of A and B are calculated using Equation (3.8) and Equation (3.9), respectively.

$$H_A = -\sum_{i=1}^{n} p_i \, log p_i \tag{3.8}$$

$$H_B = -\sum_{j=1}^{m} q_j \, log q_j \tag{3.9}$$

where p_i and q_j are the probabilities of sub-nodes. The entropy of a bottom node is 0.

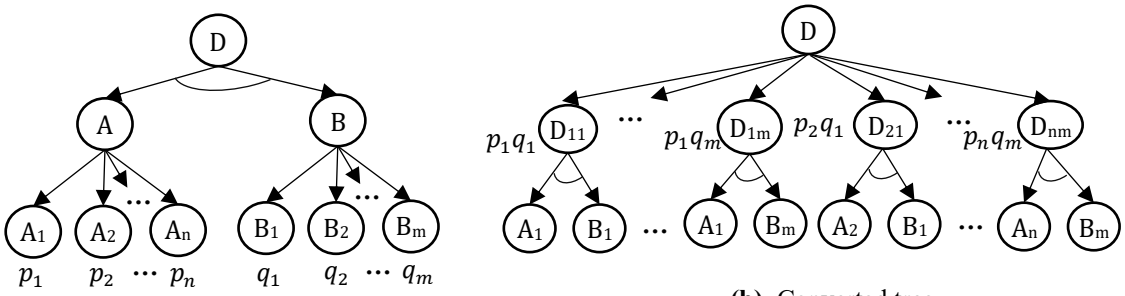


Figure 3.5. A Tree with sub-nodes in an AND relation

The AND-OR tree in Figure 3.5(a) can be converted into the tree shown in Figure 3.5(b). For $n \times m$ states with probabilities, the entropy can be calculated using Equation (3.6). The entropy of D for the tree in Figure 3.5(b) is calculated by:

$$H_D = -\sum_{j=1}^{m} p_1 \, q_j log(p_1 q_j) - \sum_{j=1}^{m} p_2 \, q_j log(p_2 q_j) - \cdots - \sum_{j=1}^{m} p_n \, q_j log(p_n q_j) \tag{3.10}$$

$$= -\sum_{j=1}^{m} p_1 \, q_j log(p_1) - \sum_{j=1}^{m} p_1 \, q_j log(q_j) - \sum_{j=1}^{m} p_2 \, q_j \log(p_2) - \sum_{j=1}^{m} p_2 \, q_j log(q_j) - \cdots - \sum_{j=1}^{m} p_n \, q_j log(p_n) - \sum_{j=1}^{m} p_n \, q_j log(q_j)$$

$$= -p_1 log(p_1) \sum_{j=1}^{m} q_j - p_1 \sum_{j=1}^{m} q_j log(q_j) - p_2 log(p_2) \sum_{j=1}^{m} q_j$$

$$-p_2 \sum_{j=1}^{m} q_j log(q_j) - \cdots - p_n log(p_n) \sum_{j=1}^{m} q_j - p_n \sum_{j=1}^{m} q_j log(q_j)$$

$$= -p_1 log(p_1) - p_2 log(p_2) - \cdots - p_n log(p_n) - (p_1 + p_2 + \cdots + p_n) \sum_{j=1}^{m} q_j log(q_j)$$

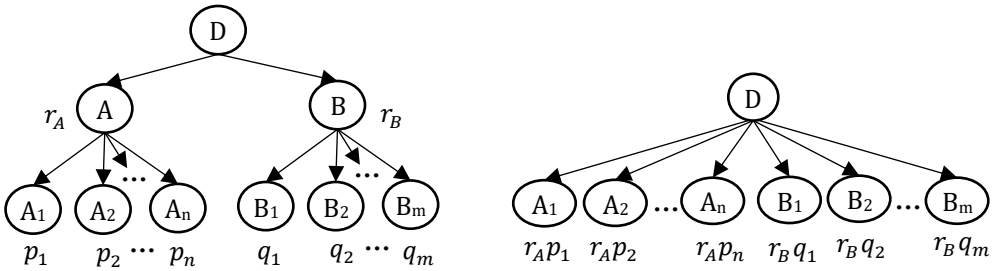
$$= -\sum_{i=1}^{n} p_i \, log(p_i) - \sum_{j=1}^{m} q_j log(q_j)$$

From Equations (3.8-3.10), we can derive Equation (3.11) considering nodes A and B with an AND ($\cap$) relation:

$$H_{A \cap B} = H_A + H_B \tag{3.11}$$

(2) Entropy of a super-node with sub-nodes in OR relation

Figure 3.6(a) shows an AND-OR tree with sub-nodes A and B in an OR relation. When a super-node is composed of sub-nodes with an OR relation, probabilities of these sub-nodes should be assigned. In Figure 3.6(a), r_A and r_B are the probabilities of A and B, respectively. Entropies of A and B are calculated using Equation (3.8) and Equation (3.9), respectively.



(a). Original tree **(b).** Converted tree

Figure 3.6. A Tree with sub-nodes in an OR relation

The AND-OR tree in Figure 3.6(a) can be converted into the tree shown in Figure 3.6(b). The entropy of D for the tree in Figure 3.6(b) is calculated by:

$$H_D = -\sum_{i=1}^{n} r_A \, p_i \, log(r_A p_i) - \sum_{j=1}^{m} r_B \, q_j log\left(r_B q_j\right) \tag{3.12}$$

$$= -r_A \, log(r_A) \sum_{i=1}^{n} p_i - r_A \sum_{i=1}^{n} p_i \, log \, p_i \; - r_B \, log(r_B) \sum_{j=1}^{m} q_j - r_B \sum_{j=1}^{m} \; q_j log q_j$$

$$= -r_A \, log(r_A) + r_A H_A - r_B \, log(r_B) + r_B H_B$$

Since $\sum_{i=1}^{n} p_i = 1$ and $\sum_{j=1}^{m} q_j = 1$, from Equations (3.8-3.9) and Equation (3.12), we can derive Equation (3.13) considering nodes A and B with an OR ($\cup$) relation:

$$H_{A \cup B} = r_A H_A + r_B H_B - (r_A log r_A + r_B log r_B) \quad (3.13)$$

(3) Entropy of an AND-OR tree

The entropy of an AND-OR tree (i.e., the entropy of the root node of the AND-OR tree) is calculated by the following rules.

- For a bottom node, its entropy is 0.
- For a super-node with *n* sub-nodes associated with an AND relation, and the entropies of the sub-nodes are $H_1, H_2, \ldots, H_n$, the entropy of the super-node is calculated by:

$$H = \sum_{i=1}^{n} H_i \quad (3.14)$$

- For a super-node with *n* sub-nodes associated with an OR relation, the entropies of the sub-nodes are $H_1, H_2, \ldots, H_n$, and the probabilities of these sub-nodes are $p_1, p_2, \ldots, p_n$, the entropy of the super-node is calculated by:

$$H = \sum_{i=1}^{n} p_i H_i - \sum_{i=1}^{n} p_i log\, p_i \quad (3.15)$$

3.3.5. The AND-OR tree for adaptation of an existing product and determination of probabilities of nodes

In this research, the nodes in an AND-OR tree for adaptation of an existing product are classified into the following two categories, design nodes and process nodes.

(a) Design nodes

A design node such as a component or an assembly describes a partial design solution. The design nodes in an AND-OR tree for product adaptation are classified into the following two categories, adaptable design nodes and unadaptable design nodes.

- *Adaptable design nodes*

  An adaptable design node can be removed, added, or replaced by another one usually with different shape and/or function for product adaptation. For example, Figure 3.7 shows the AND-OR tree of the engine unit for an internal combustion engine (ICE) car. The engine unit is composed of the engine and the bay where the engine is placed. Because the engine of the ICE car can be replaced by an electric motor for the conversion from the ICE configuration to the electric vehicle (EV) configuration, the engine is modelled by an adaptable design node.

- *Unadaptable design nodes*

  An unadaptable design node cannot be changed for product adaptation. For example, the engine bay is defined by an unadaptable design node in Figure 3.7 since it cannot be changed for product adaptation.

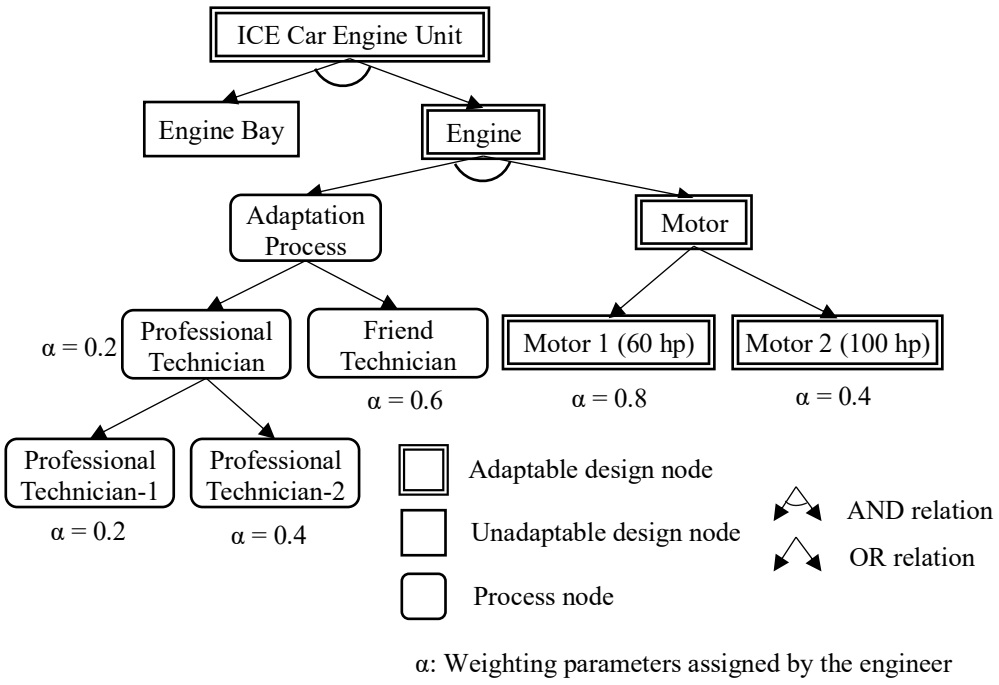


Figure 3.7. An AND-OR tree with adaptable nodes, unadaptable nodes, and process nodes

(b) Process nodes

A process node describes partial process solution for product adaptation. For example, a technician to replace the engine with the electric motor for the conversion from the ICE configuration to the EV configuration is modelled by a process node as shown in Figure 3.7.

For calculation of entropies of the branches of the AND-OR tree, probabilities of sub-nodes with OR relations need to be determined first. When a node is composed of sub-nodes with an OR relation, the sum of probabilities of these sub-nodes should be 1. When the number of sub-nodes is large, determination of probabilities of these sub-nodes could be a challenging task. To solve this problem, probabilities of nodes with OR relations are determined through 2 steps, assignment of weighting parameters and calculation of probabilities.

(1) Assignment of weighting parameters for sub-nodes associated with an OR relation

For a design/process super-node with *n* sub-nodes associated with an OR relation, a weighting parameter α_i between 0 and 1 is assigned by engineers for each sub-node representing the possibility of the *i-th* sub-node to be selected without considering the influence of other sub-nodes. A weighting parameter can be the availability of a resource or satisfaction to a partial solution. For example, Motor 1 and Motor 2 in Figure 3.7 are assigned with weighting parameters of 0.8 and 0.4, respectively based on satisfaction measures of these solutions considering costs. Friend Technician, Professional Technician-1 and Professional Technician-2 are assigned with weighting parameters of 0.6, 0.2 and 0.4, respectively based on the availabilities of these technicians.

In this research, the following rules are used to determine the weighting parameter of a node in an AND-OR tree for product adaptation:

- Weighting parameters are assigned to only adaptable design sub-nodes associated with an OR relation, and process sub-nodes associated with an OR relation.
- An unadaptable design node cannot have sub-nodes associated with an OR relation since different solutions for the original configuration before product adaptation are not considered for adaptation of an existing product.

(2) Calculation of probabilities for sub-nodes associated with an OR relation

For a super-node with *n* sub-nodes that are associated with an OR relation, because each sub-node is assigned a weighting parameter α_i, the probability of the *i-th* sub-node for entropy calculation is obtained by:

$$p_i = \frac{\alpha_i}{\sum_{i=1}^{n} \alpha_i} \tag{3.16}$$

where the summation of probabilities for the *n* sub-nodes of the super-node is equal to 1.

The entropy of the AND-OR tree for adaptation of an existing product is then calculated using Equations (3.8-3.15) and the rules explained earlier in Section 3.3.4. The results calculated from the AND-OR tree shown in Figure 3.7 are summarized in Table 3.1.

Table 3.1. Results for the AND-OR tree in Figure 3.7

Design/Process node	Type of node	Weighting parameter (α)	Probability (p)	Entropy (H)
Professional Technician-1	Process node	0.2	0.33	0
Professional Technician-2	Process node	0.4	0.67	0
Professional Technician	Process node	0.2	0.25	0.64
Friend Technician	Process node	0.6	0.75	0
Adaptation Process	Process node	-	-	0.72
Motor 1 (60 hp)	Adaptable design node	0.8	0.67	0
Motor 2 (100 hp)	Adaptable design node	0.4	0.33	0
Motor	Adaptable design node	-	-	0.64
Engine	Adaptable design node	-	-	1.36
Engine Bay	Unadaptable design node	-	-	0
ICE Car Engine Unit	Adaptable design node	-	-	1.36

3.3.6. A numerical example

To illustrate the effectiveness of the entropy-based method to evaluate the information quality of AND-OR tree branches, a numerical example was created and evaluated by simulation using MATLAB through comparison of two sub-trees with similar computation effort but different entropies. In this example, two AND-OR sub-trees (i.e., branches of an AND-OR tree) were created as shown in Figure 3.8. Tree A has 18 possible solutions, while Tree B has 24 solutions.

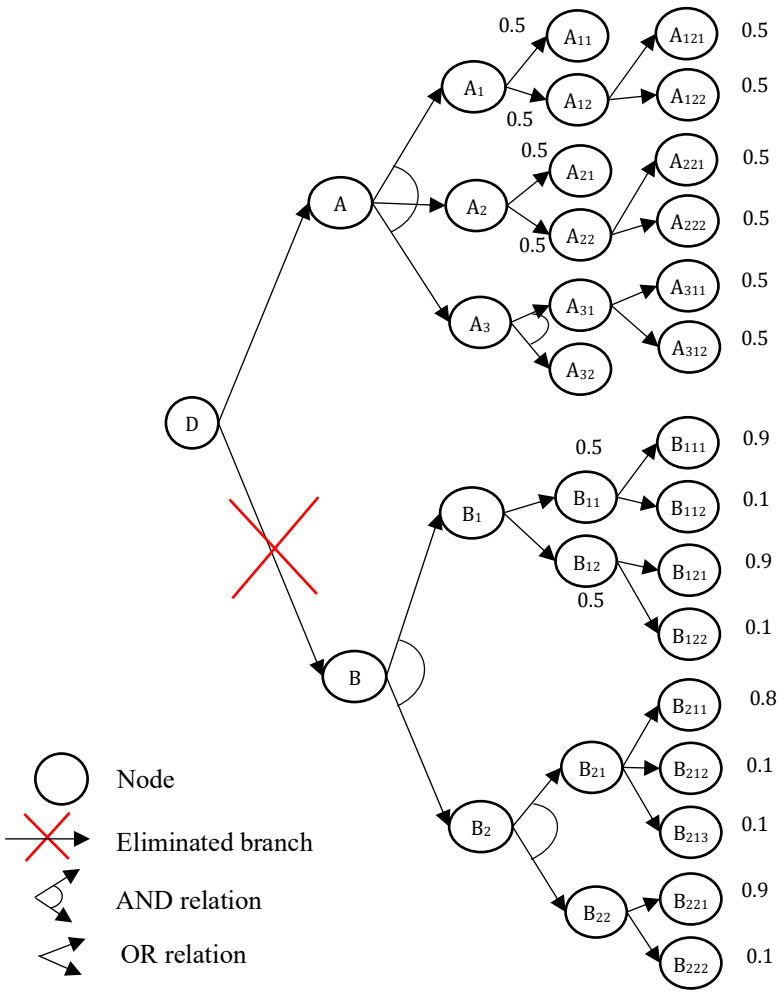


Figure 3.8. An AND-OR tree with two branches of sub-trees

The nodes of Tree A have similar probabilities, while the nodes of Tree B have quite different probabilities. Using these probabilities, information entropy was calculated for each tree based on the method described in Section 3.3.4. The results have shown that Tree A has higher entropy, and hence a higher number of contributing (true or effective) solutions. Therefore, Tree A has a better chance to obtain the optimal solution. Nominal numbers of solutions, entropies and effective numbers of solutions for Tree A and Tree B are summarized in Table 3.2.

Table 3.2. Comparison between Tree A and Tree B

Item	Tree A	Tree B
Nominal number of solutions	18	24
Entropy (H)	2.7726	1.6684
Effective number of solutions (N)	16.0000	5.0637

The Tree A and Tree B for the comparative study to evaluate optimization quality satisfied the following conditions:

- Tree A and Tree B were with the similar structures (i.e., similar numbers of nodes, numbers of layers, numbers of AND-OR relations, and numbers of solutions) requiring similar computation efforts.
- The best solutions for Tree A and Tree B were with similar best evaluation measures.

The goal of the comparative study was to evaluate the chances to obtain the optimal solutions using Tree A and Tree B with the similar computation efforts.

When the real-world adaptable product design cases are used for the comparative study, since different configurations/processes are created from Tree A and Tree B in configuration/process optimization, the optimal evaluation measures for Tree A and Tree B achieved in parameter optimization are usually different, leading to the difficulty to satisfy the second condition for the comparative study. Therefore, only a numerical example was used for this comparative study.

Numerical tests were conducted to validate this conclusion. First for each of the solutions, a random value between 0 and 1 was assigned as the evaluation measure. Then n solutions were selected randomly based on the probabilities of these solutions calculated from the probabilities of the nodes to see whether the solution with the best evaluation measure can be obtained from these n solutions. Please note the same solution can be selected multiple times in the test. The test with n solutions was repeated 10,000 times, and the probability to obtain the optimal solution from the n solution was obtained. For example, when n is selected as 10, the probability to obtain the optimal solution for Tree A was 0.4082, while the probability to obtain the optimal solution for Tree B was 0.2008, as shown in Table 3.3.

Table 3.3. Probabilities to obtain the optimal solution using each tree (No. of samples = 10,000)

Number of random solutions	Probability to obtain the optimal solution	
	Tree A	**Tree B**
1	0.0556	0.0421
2	0.1064	0.0734
3	0.1563	0.1051
4	0.2065	0.1205
5	0.2369	0.1442
6	0.2784	0.1558
7	0.3110	0.1754
8	0.3504	0.1807
9	0.3797	0.1994
10	0.4082	0.2008
20	0.6314	0.3068
30	0.7621	0.3720
40	0.8407	0.4263
50	0.8950	0.4564
100	0.9803	0.5605
200	0.9998	0.6783

Numerical tests with other n values are shown in Table 3.3. From this table, we can see that when n is small, the probability of obtaining the optimal solution in each tree is small and random. With increase of the value of n, the probability of obtaining the optimal solution is also increased. For Tree A, the probability to obtain the optimal solution is higher than the probability to obtain the optimal solution for Tree B, particularly when n is high. This is because all the solutions in Tree A have similar chances to be selected for evaluation, while smaller number of solutions in Tree B have chances to be selected. Therefore, Tree A provides better useful information to obtain the optimal solution because of its larger entropy than Tree B.

For an AND-OR tree with many branches, the number of branches to be pruned can be determined based on an optimization time constraint. For instance, if an AND-OR tree has ten branches each with multiple feasible solutions, and each branch requires one second for parameter optimization, but only five seconds are available. Then the five branches with the lowest entropy values are removed, and only the remaining five are used in tree-based search. This approach is essential in cases such as control system tuning and finite element analysis (FEA), where the computation or simulation time for each configuration is significant. Thus, the developed approach

for pruning of AND-OR tree branches based on information entropy balances solution quality and computational efficiency within the available optimization time constraints.

3.4. A Case Study: Conversion of an Existing Internal Combustion Engine (ICE) Vehicle into an Electric Vehicle (EV)

An engineering application case study was developed to demonstrate the effectiveness of the newly introduced optimal adaptable product design approach with initial evaluation of the configurations/processes modelled by AND-OR trees based on information entropy.

3.4.1. Problem of the product adaptation

The objective of this case study was to convert an existing internal combustion engine (ICE) vehicle into an electric vehicle (EV). The activities for the conversion of ICE cars into EV cars have become popular practices in recent years. Although most of these activities are carried out as do-it-yourself (DIY) projects for hobbies to promote environmental awareness, these activities have potential economic value since many governments have introduced new policies, such as carbon taxes, to eliminate the use of traditional ICE cars in the near future. In 2023, the government of Canada announced an Electric Vehicle Availability Standard with regulated targets for zero-emission vehicles (ZEVs). Under this standard, the targets for sales of the ZEVs will be 20% in 2026, 60% in 2030, and 100% in 2035.

The major difference between an ICE car and an EV car is that an electric vehicle is composed of an electric motor, a battery pack and a control panel compared with the engine, fuel tank, exhaust system, etc. used for an ICE car. The conversion happens usually to the ICE cars when their engines reach their end of lifespan, although these cars are still in good conditions structurally. To convert an ICE car into an EV car, we need to remove the ICE parts and replace them with the EV parts as shown in Figure 3.9. Each module can be selected from options of different types, suppliers, and qualities with different contributions to the evaluation measures of this project. In addition to the selection of parts for product adaptation, selection of product adaptation process was also considered in this case study.

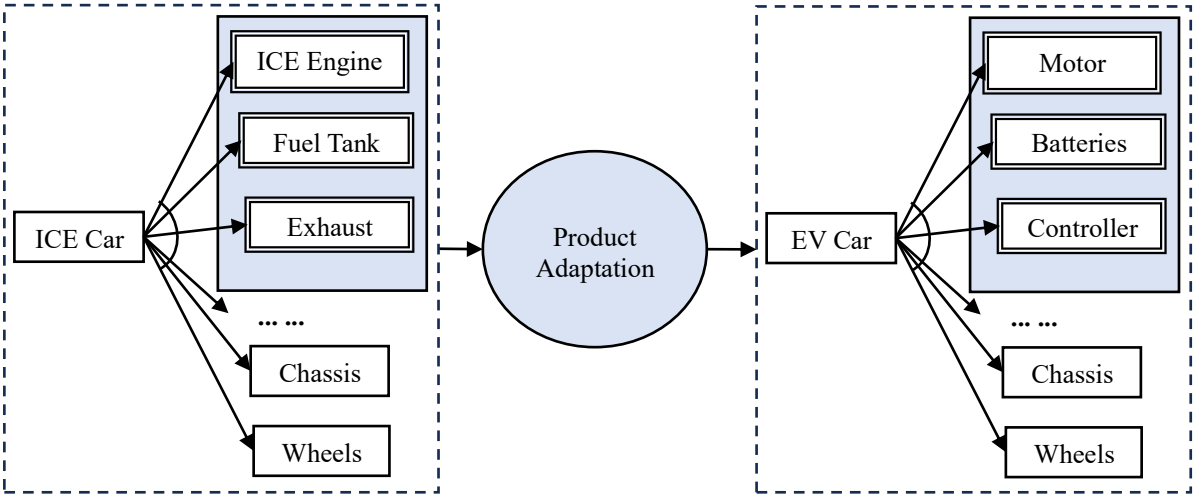


Figure 3.9. Product adaptation for the ICE car

In this work, two scenarios were considered to convert an ICE vehicle into an electric vehicle, and a decision needs to be taken to select the scenario that is most likely to have the optimal solution using the proposed entropy-based approach.

- **Scenario A: Adaptation of ICE vehicle into EV by a professional mechanics shop**

  Since the professional mechanics shops usually deal with specific suppliers and delivery agents, the probabilities to select different suppliers, components, and delivery agents are usually quite different.

- **Scenario B: Adaptation of ICE vehicle into EV by a DIY project with help from a mechanics friend**

  Since the customer and the mechanics friend usually don't have significant preferences for selection of suppliers and delivery agents, the probabilities to select these different suppliers, components, and delivery agencies are usually not significantly different.

3.4.2. Modelling of design configurations, adaptation processes, and parameters of configurations and processes

In this work, an AND-OR tree was used to model the generic design and process alternatives as shown in Figure 3.10. The Tree A for Scenario A and the Tree B for Scenario B have the same AND-OR tree data structure, but with different probabilities to select different design and process

nodes. Nodes in the AND-OR trees included adaptable design nodes for the adapted product design, unadaptable design nodes, and product adaptation process nodes. Probabilities for unadaptable design nodes were not considered in this research, since these nodes were not considered to be changed during product adaptation.

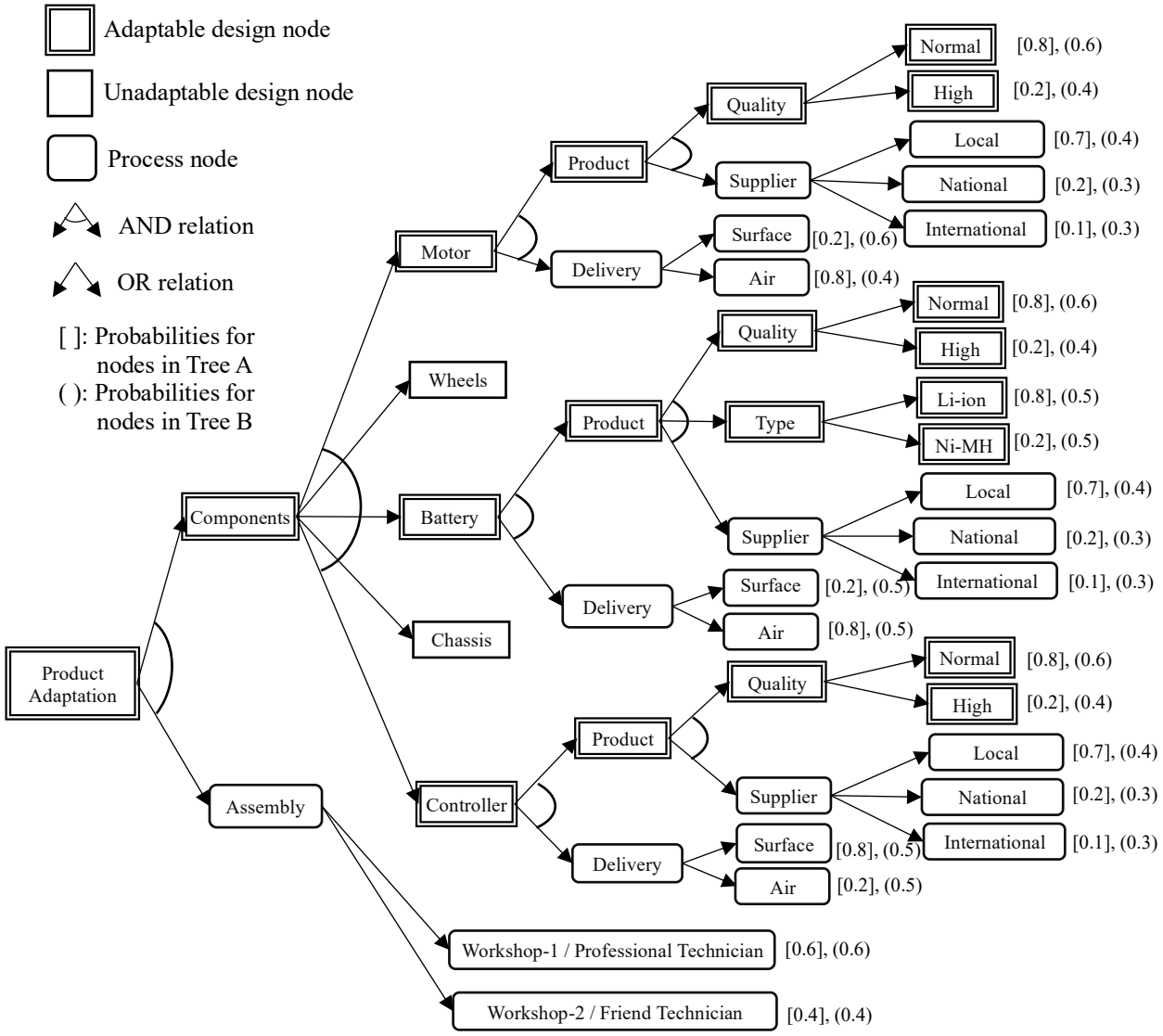


Figure 3.10. Two generic AND-OR trees for adapting an ICE car into an electric vehicle

Tree A for adaptation by a professional mechanics shop was modelled by nodes with different probabilities due to the strong preferences of mechanics technicians. Tree B for adaptation was modelled by nodes with similar probabilities since the customer and the technician friend didn't have strong preferences. From the AND-OR tree, a total of 6,912 solution candidates with the

adapted design configurations and the product adaptation processes were created through tree-based search for each scenario.

Entropies *H* and effective numbers of solutions *N* for the two trees were calculated as follows.

- **Tree A:**

  $H_A = 6.5813$, $N_A = 721.5$

- **Tree B:**

  $H_B = 8.7313$, $N_B = 6194.0$

From the above results, Tree B provides more effective solutions for adaptation of the ICE to EV. Therefore, Tree B has a better opportunity than Tree A to get the optimal solution.

Each design/process solution was modelled by nodes with design parameters and process parameters. Various databases were created to model the available components (e.g., motors, batteries, and controllers) at different suppliers, the services at delivery companies, mechanics shops, and technicians based on information in this market (Toms 2021). The database for available batteries from a national supplier is shown in Table 3.4.

Table 3.4. Available batteries in a national supplier

Model	Type	Energy (kWh)	Quality	Cost ($)
B1	Li-ion	1.5	Normal	450
B2	Li-ion	2.0	Normal	600
B3	Li-ion	3.0	Normal	900
B4	Li-ion	5.0	Normal	1300
B5	Li-ion	1.5	High	350
B6	Li-ion	2.0	High	500
B7	Li-ion	3.0	High	700
B8	Li-ion	4.0	High	1000
B9	NiMH	1.5	Normal	300
B10	NiMH	2.0	Normal	350
B11	NiMH	2.5	Normal	450
B12	NiMH	3.0	Normal	550
B13	NiMH	1.5	High	250
B14	NiMH	2.0	High	250
B15	NiMH	3.0	High	350

In this case study, two design parameters were selected as variables for parameter optimization.

- *P:* Power of the electric motor (*hp*)
- *N*: Number of batteries (*integer*)

3.4.3. Evaluation and optimization

Five evaluation measures were selected for evaluation of the design and process solutions.

- C_T: Total cost of adaptation (modules and processes) (*$*)
- D_T: Total duration (*day*)
- A_t: Acceleration time of the electric vehicle (*second*)
- *R*: Reliability (*%*)
- D_R: Distance range of the EV (*km*)

The evaluation measures were calculated from the design parameters. The total cost C_T was obtained by:

$$C_T = C_{configuration} + C_{process} \tag{3.17}$$

where $C_{configuration}$ is the cost of components for the design configuration, and $C_{process}$ is the cost of the adaptation process. The cost of configuration was calculated by:

$$C_{configuration} = C_{motor} + C_{battery\text{-}pack} + C_{controller} \tag{3.18}$$

where in each configuration, C_{motor} *($)* is the cost of the selected motor, $C_{battery\text{-}pack}$ *($)* is the cost of the battery pack, and $C_{controller}$ *($)* is the cost of the controller. The cost of battery pack was calculated by:

$$C_{battery\text{-}pack} = C_{battery\text{-}unit} \times N \tag{3.19}$$

where $C_{battery\text{-}unit}$ is the cost of a unit battery. The cost of the corresponding adaptation process was calculated by:

$$C_{process} = C_{motor\text{-}delivery} + C_{battery\text{-}delivery} + C_{controller\text{-}delivery} + C_{assembly} \tag{3.20}$$

where $C_{motor\text{-}delivery}$ is the cost for motor delivery, $C_{battery\text{-}delivery}$ is the cost for battery delivery, $C_{controller\text{-}delivery}$ is the cost for controller delivery, and $C_{assembly}$ is the cost for assembly adaptation process.

The total duration (*days*) of the adaptation was calculated by:

$$D_T = max\{D_{motor\text{-}delivery}, D_{battery\text{-}delivery}, D_{controller\text{-}delivery}\} + D_{assembly} \quad (3.21)$$

where $D_{motor\text{-}delivery}$ is the duration for motor delivery, $D_{battery\text{-}delivery}$ is the duration for battery delivery, $D_{controller\text{-}delivery}$ is the duration for controller delivery, and $D_{assembly}$ is the duration for assembly adaptation process.

The acceleration time A_t (*seconds*) for the electric vehicle to reach 60 km/hour from 0 km/hour was achieved by:

$$A_t = \frac{M\left(v \times \frac{1000}{3600}\right)^2}{2 \times (746\ P)} \quad (3.22)$$

where M is the mass of the electric vehicle (kg) which was assumed as 2000 kg, v is the average speed of an electric vehicle which is approximately 60 km/hour, and P is the power of the selected motor (*hp*).

The five-year reliability measure (%) of the electric vehicle was calculated by:

$$R = R_{motor} \times (R_{battery})^N \times R_{controller} \quad (3.23)$$

where R_{motor} *(%)* is the reliability of the selected motor, $R_{battery}$ *(%)* is the reliability of the battery unit, and $R_{controller}$ *(%)* is the reliability of the controller. In this work, the probability that a module would not fail within 5 years was selected as the reliability measure.

The distance range D_R (*km*) of the EV to travel when the battery is fully charged was calculated by:

$$D_R = \frac{E_B.N}{e_{avg}} \quad (3.24)$$

where E_B is the energy of the battery (*kw-hour/battery*), and e_{avg} is the average energy consumption of an electric vehicle which was assumed to be 0.2 kw-hour/km.

Since five evaluation measures with different units were considered in this case study, these five evaluation measures were converted into five comparable evaluation indices to build the overall evaluation index considering importance factors of these evaluation indices. In this work, satisfaction indices were used as the evaluation indices. First, data points considering evaluation measures and evaluation indices were obtained from customers and engineers. The least-squares curve fitting method was then used to obtain the numerical relations (Yang et al. 2006). Figure 3.11 shows the data points and the fitted curves to model the relations between the five evaluation measures and their corresponding evaluation indices.

The five evaluation indices were achieved as:

$$I_{C_T} = 1 - \frac{1}{80000} C_T \tag{3.25}$$

$$I_{D_T} = -1.5006 \times 10^{-8} D_T^4 + 2.5534 \times 10^{-6} D_T^3 - 2.5039 \times 10^{-4} D_T^2 + 0.0048 D_T + 0.9725 \tag{3.26}$$

$$I_{A_t} = -2.2145 \times 10^{-4} A_t^4 + 0.0052 A_t^3 - 0.0451 A_t^2 + 0.0503 A_t + 0.9917 \tag{3.27}$$

$$I_R = -3.9336 \times 10^{-8} R^4 + 6.012 \times 10^{-6} R^3 - 1.4781 \times 10^{-4} R^2 + 0.0040 R - 0.0027 \tag{3.28}$$

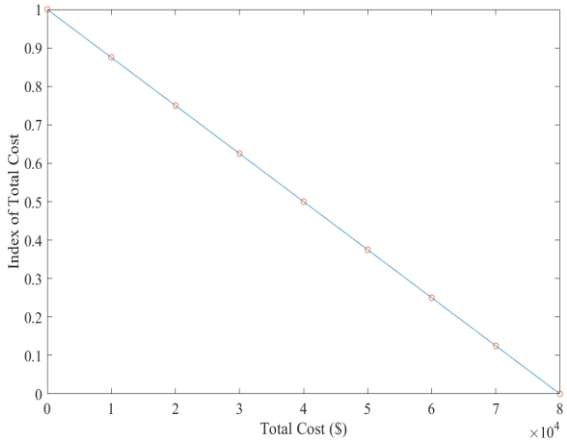
$$I_{D_R} = -2.626 \times 10^{-10} D_R^4 + 1.114 \times 10^{-7} D_R^3 - 5.407 \times 10^{-7} D_R^2 + 5.570 \times 10^{-4} D_R - 0.0027 \tag{3.29}$$

The overall evaluation index *I* was defined by:

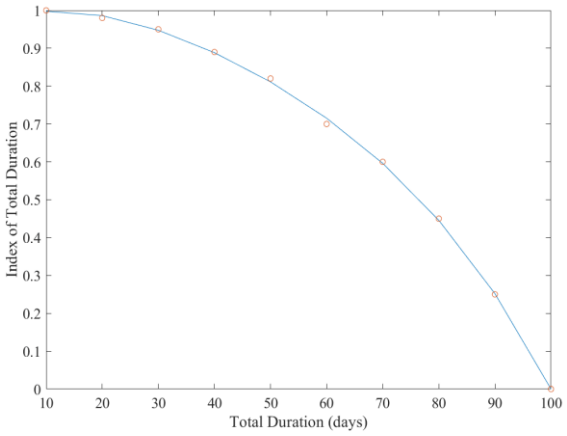
$$I = \frac{W_{C_T} I_{C_T} + W_{D_T} I_{D_T} + W_{A_t} I_{A_t} + I_R W_R + W_{D_R} I_{D_R}}{W_{C_T} + W_{D_T} + W_{A_t} + W_R + W_{D_R}} \tag{3.30}$$

where the weighting factors for these five evaluation indices were selected as:

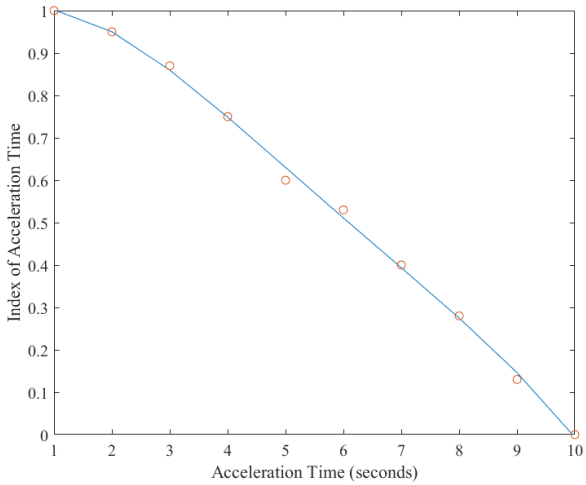
$W_{C_T} = 0.5, W_{D_T} = 0.3, W_{A_t} = 0.2, W_R = 0.2, W_{D_R} = 0.2$



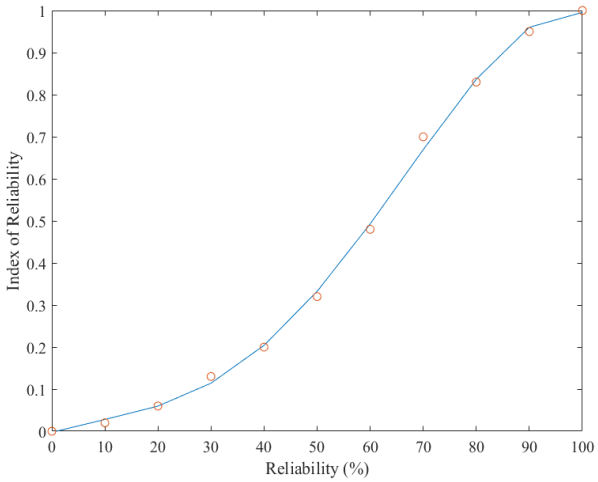
(a). Total cost and its index



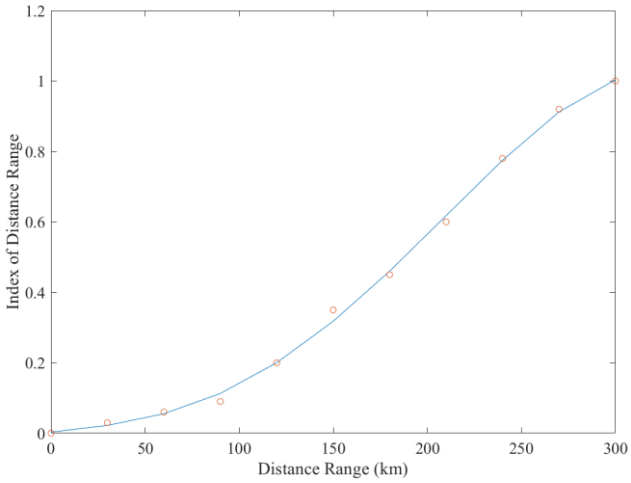
(b). Total duration and its index



(c). Acceleration time and its index



(d). Reliability and its index



(e). Distance range and its index

Figure 3.11. Evaluation measures and their evaluation indices

The multi-level optimization (Xue 1997) was then carried out to identify the optimal solution and its optimal parameter values with the maximum overall evaluation index *I*. In this work, the parameter optimization was defined by:

$$\max_{w.r.t.\ (P,N)} I(P,N) \quad (3.31)$$

$$s.t.$$

$$60 \le P \le 200$$

$$10 \le N \le 30$$

Through multi-level optimization, the optimal solution was achieved as:

- **Design configuration in the optimal solution:**

  Motor quality = High

  Battery quality = High

  Battery type = Ni-MH

  Controller quality = Normal

- **Adaptation process in the optimal solution:**

  Motor supplier = National

  Motor delivery = Air

  Battery supplier = Local

  Battery delivery = Surface

  Controller supplier = National

  Controller delivery = Air

  Assembly = Workshop-2 / Friend Technician

- **The optimal parameter values:**

  P = 130 hp

  N= 15 batteries

The evaluation measures and their evaluation indices corresponding to the optimal solution are shown in Table 3.5.

Table 3.5. Evaluation measures and evaluation indices for the optimal solution

Evaluation measure	Optimal value	Optimal index
Total cost ($)	27,350	0.6581
Total duration (days)	45	0.8520
Acceleration time (s)	3.10	0.8490
Reliability (%)	0.70	0.6730
Distance range (km)	225	0.6975
Overall evaluation index		**0.7347**

3.5. Summary

An efficient optimization approach was developed in this chapter to identify the adapted product design and the product adaptation process with initial evaluation of information quality in branches of an AND-OR tree based on information entropy. In this work, a procedure for adaptation of existing products was also presented. The adapted product design candidates and the adaptation process candidates, in addition to parameters associated with product configurations and adaptation processes, were modelled using an AND-OR tree. The adapted product design configuration candidates and the product adaptation process candidates were evaluated using multiple evaluation measures. Information entropy was employed to evaluate information quality in branches of the AND-OR tree for improving optimization efficiency by pruning the branches with less useful information. The optimal adapted product design configuration candidate, the optimal adaptation process candidate, and the optimal configuration/process parameter values were then identified through the two-level optimization method. A numerical example and an engineering application case study have been conducted to demonstrate the effectiveness of this developed method.

The characteristics of this newly developed method are summarized as follows.

(1) Information entropy is an effective measure to evaluate the quality of information for an AND-OR tree. For an AND-OR tree composed of many nodes with limited availabilities to be selected to create the design and process solutions, the effective number of solutions from this tree is actually smaller than the nominal number of solutions created through tree-based search.

(2) Evaluation of branches in an AND-OR tree based on information entropy is effective to remove branches with less useful information leading to the optimal solution. By pruning the branches of an AND-OR tree with smaller entropies, efficiency of optimization to obtain the optimal solution can be improved significantly.

(3) The optimal design and process planning approach developed in this research is effective to identify the optimal adapted design configuration, the optimal adaptation process, and the optimal values of design and process parameters for product adaptation.

In the next chapter, in addition to the creation of the adapted designs for adaptation of the existing products, design of new adaptable products that can be easily changed during product operation stages will be investigated. The new design approach will be employed for the design of a new internal combustion engine (ICE) vehicle that can be easily converted into an electric vehicle (EV).

Chapter 4. Design of New Adaptable Products Considering the Original Product Design Configurations, the Adapted Product Design Configurations, and the Product Adaptation Processes

4.1. Introduction

Adaptable products can be changed in configurations and parameters during their operation stages to satisfy changes in functional requirements and environmental conditions. The objective for the design of adaptable products is to reduce the time and cost of product adaptation in the operation stages.

In Chapter 3, design for adaptation of existing products was considered. The efforts needed for adaptation of existing products during their operation stages, however, can be high since product adaptation was not considered during the design stages of these products. As a result, the existing products sometimes cannot be changed to satisfy the new requirements, and new products need to be designed and manufactured. Since approximately 80% of the costs related with a product's lifecycle are determined in the early design stages, while the design phase itself takes only 20% of the overall effort to product development (O'Grady and Young 1991; Niu et al. 2022), design of new adaptable products, instead of modification of the existing ones, can lead to reduction of the adaptation efforts to satisfy new customer requirements.

The objective of this chapter is to develop a new method for optimal design of new adaptable products to identify the original product design configuration before adaptation, the adapted design configuration after adaptation, and the product adaptation process, as well as the configuration/process parameter values.

The key difference between the work carried out in Chapter 3 and the work that will be presented in Chapter 4 is summarized as follows.

- In Chapter 3, the scope of adaptable product design was limited to the adaptation of existing products, where multiple adapted product design solutions were created and evaluated for selection of the optimal one.
- In Chapter 4, the scope of adaptable product design is extended to the design of new adaptable products, where multiple design solutions of the original product configuration before product

adaptation are also considered in addition to the multiple design solutions of the adapted product configuration for each of the original product design configurations for selection of the optimal original product design configuration and adapted product design configuration. Same as Chapter 3, the product adaptation processes are also considered in this chapter.

4.2. A New Method for Identification of the Optimal Original Design Configuration, Adapted Design Configuration, and Product Adaptation Process for the Design of a New Adaptable Product

In this section, first a framework is developed to integrate the tasks of design for adaptation of existing products and the tasks for the design of new adaptable products in the same environment. Second, the procedure for the design of new adaptable products for easy product adaptation is explained.

4.2.1. Framework of the developed method

The framework of this new method for identification of the optimal original design configuration, adapted design configuration, and product adaptation process is shown in Figure 4.1. Design tasks in this framework are classified into two categories: design for adaptation of an existing product and design of a new adaptable product.

- *Design for adaptation of existing products*

  In this type of design, an existing product (e.g., a Toyota Camry) is selected for product adaptation (e.g., to convert from an internal combustion engine (ICE) car to an electric vehicle (EV) car). First, the design of the existing product is selected, and an AND-OR tree is used to model the original configuration of the existing product and all possible adapted design configurations, adaptation processes, and parameters of the adapted design configurations and the adaptation processes. The multi-level optimization is then conducted to identify the optimal adapted design configuration, adaptation process, and parameters of the adapted design configuration and the adaptation process. The optimal solution is subsequently used to convert the existing product from the original configuration (e.g., the ICE Toyota Camry) to the adapted configuration (e.g., the converted EV Toyota Camry).

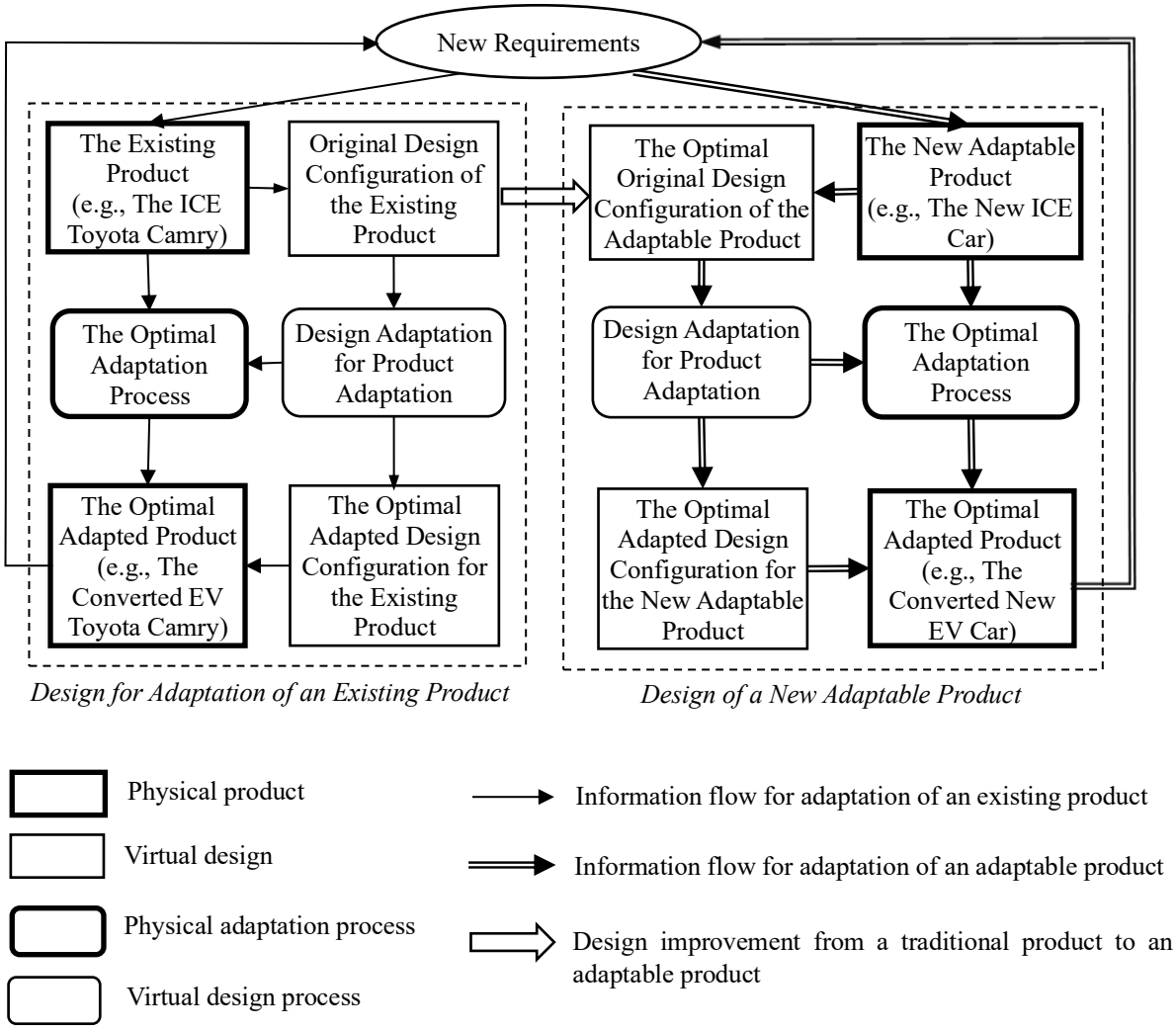


Figure 4.1. Framework of the developed method

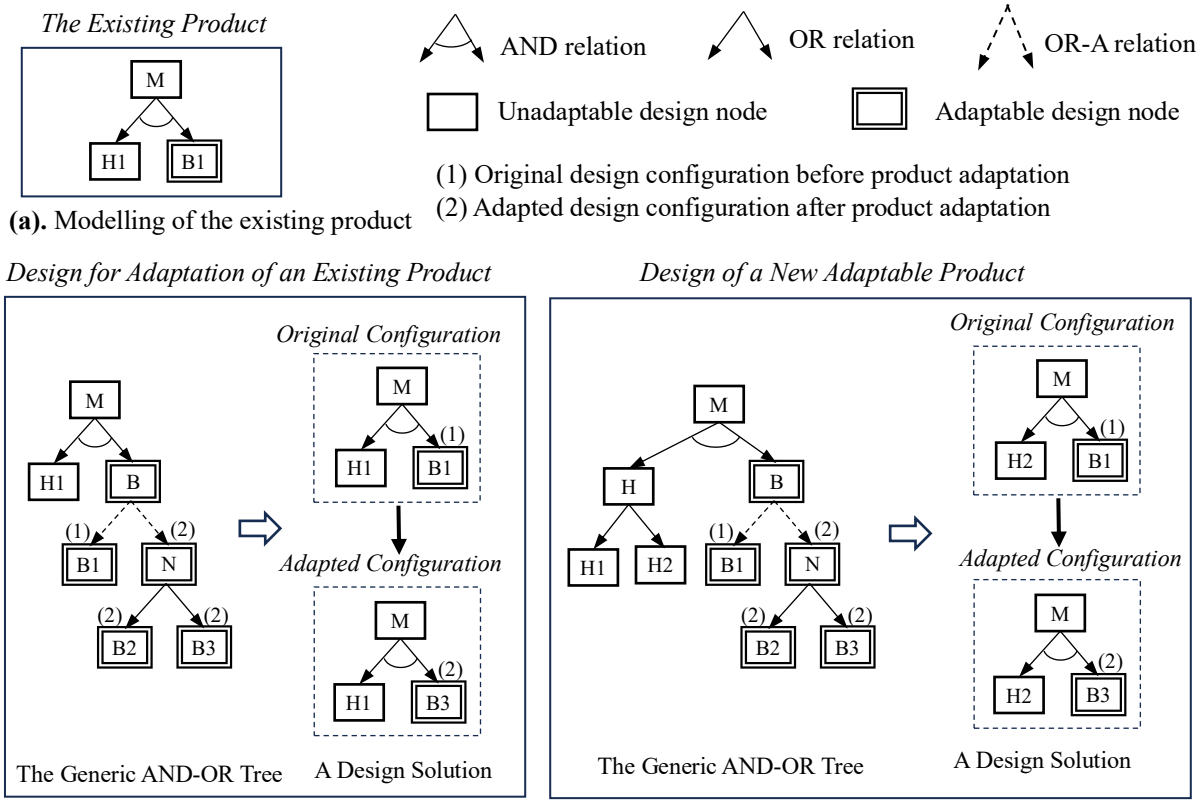
- *Design of new adaptable products*

In this type of design, an existing product (e.g., a Toyota Camry) is used as a baseline for the design of the new adaptable product through design improvement. First, the existing product is considered to define an AND-OR tree for modelling the new generic adaptable product by considering all possible solutions with the original design configurations, the adapted design configurations, the product adaptation processes, and the parameters of these configurations and processes. The multi-level optimization is then conducted to identify the optimal original design configuration, adapted design configuration, product adaptation process, and configuration/process parameters. The optimal original design configuration is subsequently used for manufacturing of the original configuration of the adaptable product (e.g., the new

ICE vehicle). When product adaptation is required in the operation stage, the optimal adapted design configuration and product adaptation process are then used to convert the original configuration of the adaptable product (e.g., the new ICE car) into the adapted configuration of this adaptable product (e.g., the converted new EV car) to satisfy the customer requirements.

In this work, the virtual solution is called design or product design (e.g., adaptable design or adaptable product design), while the physical solution is called product (e.g., adaptable product), as shown in Figure 4.1.

Differences between the design for adaptation of an existing product and the design of a new adaptable product in modelling are illustrated with simple examples as shown in Figure 4.2. First, the existing product is selected and design of this existing product is modelled by a tree as shown in Figure 4.2(a). In this existing product, H1 is the battery housing of a cell phone, and B1 is the battery of the cell phone. The adaptation requirement is to upgrade the existing battery B1 to a new one with higher power density.



(a). Modelling of the existing product

(b). Design for adaptation of an existing product

(c). Design of a new adaptable product

Figure 4.2. Differences between design for adaptation of an existing product and design of a new adaptable product

In the process of the design for adaptation of an existing product as shown in Figure 4.2(b), the tree of the existing product is modified as the generic AND-OR tree, considering different design solutions to adapt the existing product. In this example, two batteries, B2 and B3, are considered for upgrade. From the generic AND-OR tree, two solutions (i.e., one with B2 and one with B3) are created through tree-based search for product adaptation. When B3 is better than B2, considering performance or cost, the solution with B3 is selected as the design solution. The B3 is then used to upgrade B1 in the original design configuration to the adapted design configuration. Since the battery housing may not be designed particularly for battery upgrade, some efforts (e.g., service of a skilled technician) are required for the battery upgrade.

In the process of designing an adapted product, as shown in Figure 4.2(c), the design of a new original product configuration is also considered in addition to product adaptation. In this case, the tree of the existing product is modified into the generic AND-OR tree, considering different original product design configurations and different adapted product design configurations. In the example shown in Figure 4.2(c), two different battery housing units, H1 and H2, are considered for the original product design configuration, in addition to the two batteries, B2 and B3, for the adapted product design configuration. From the generic AND-OR tree, two solutions for the original product design configuration (i.e., one with H1 and one with H2) are created, and each of these original product design configurations can be further changed into the two adapted product design configurations (i.e., one with B2 and one with B3). Suppose H2 is the battery housing appropriate for battery upgrade by the customers, H2 is then selected for the original product design configuration, considering its better battery adaptation function.

From the examples shown in Figure 4.2, we can see that the objective for the design of the adaptable product is to design a new original configuration of the product that can be easily adapted. Although the cost of the original configuration for an adaptable product is often higher than the cost of the traditional product, the cost of the adaptation process for the adaptable product is expected to be much lower, thus leading to the reduction of the total cost. In the case study given in Chapter 3, the adaptation of an existing Toyota Camry from the ICE car to the EV car was conducted. The objective for the new adaptable design approach is to design a new ICE car that can be easily adapted to an EV car.

4.2.2. The procedure for the design of new adaptable products

In this section, the procedure for the design of new adaptable products is presented as follows.

4.2.2.1. Modelling for the design of adaptable products

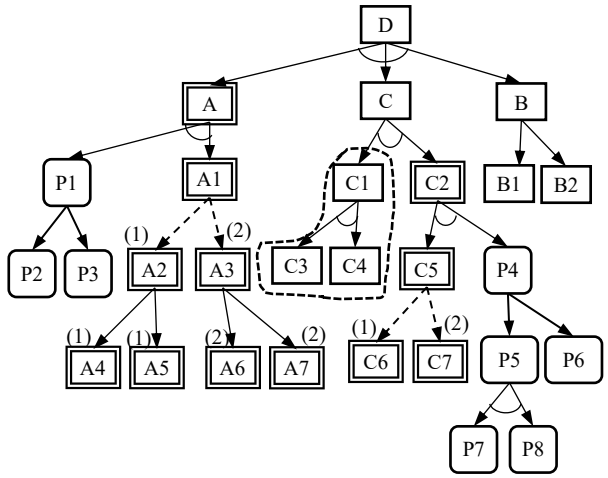
Changes of models for the design of an adaptable product are shown in Figure 4.3.

(a) Modelling of the generic product with alternative solutions of the original design configurations, the adapted design configurations and the product adaptation processes

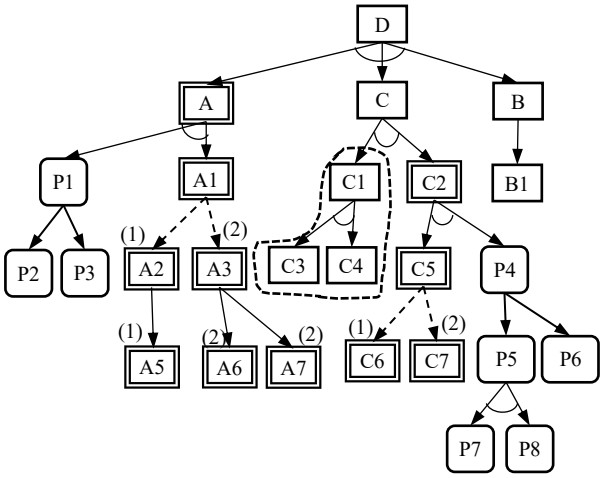
The generic product with all possible original design configurations, adapted design configurations, and adaptation processes is modelled by an AND-OR tree as shown in Figure 4.3(a). Nodes of the tree are defined by design nodes and process nodes. Partial design solutions, such as components and sub-assemblies, are described by the design nodes, while partial adaptation process solutions, such as assembly operations and disassembly operations, are described by the process nodes. Design nodes are classified into the following two categories, unadaptable design nodes and adaptable design nodes.

- *Unadaptable design nodes:* nodes that cannot be modified (e.g., replaced or removed) for product adaptation.
- *Adaptable design nodes:* nodes that can be changed for product adaptation.

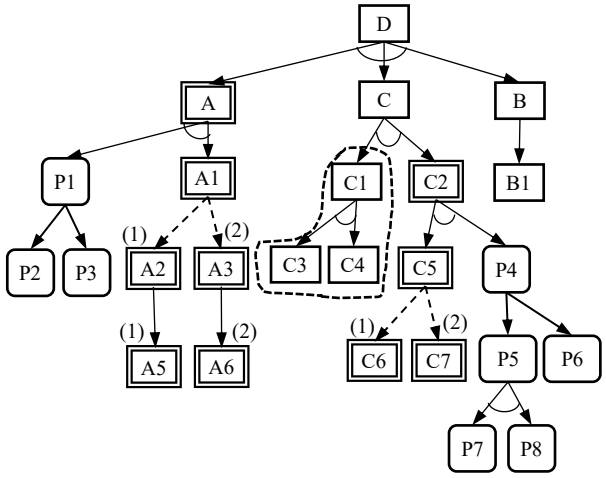
When a collection of design nodes is grouped into a module, nodes in this module cannot be separated in product adaptation. Sub-nodes of a super-node are associated with three types of relations: AND relation when all the sub-nodes need to be selected to support the super-node, OR relation when only one sub-node needs to be selected to support the super-node, and OR-A (i.e., OR for adaptation) relation when different sub-nodes are used for different configurations of the product by considering product adaptation. In this work, only two configurations for the original design before product adaptation and the adapted design after product adaptation are considered.



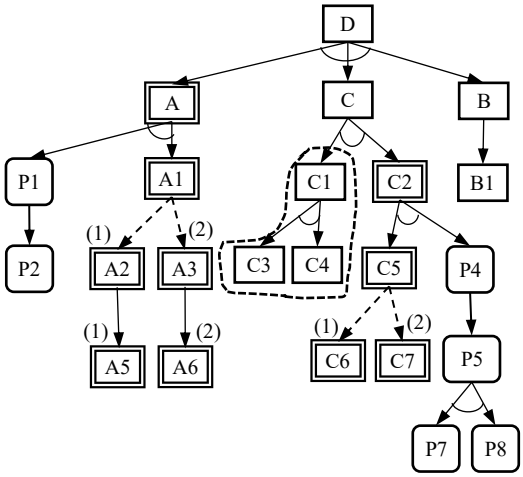
(a). An AND-OR tree for modelling of generic product with alternative solutions of original design configurations, adapted design configurations and product adaptation processes



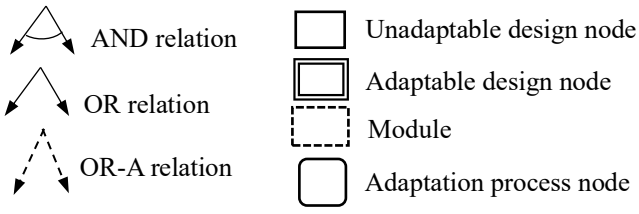
(b). A specific original design configuration with alternative solutions of adapted design configurations and adaptation processes created from the model in (a)



(c). A solution with a specific original design configuration, a specific adapted design configuration, and alternative adaptation processes created from the model in (b)



(d). A final solution with a specific original design configuration, a specific adapted design configuration, and a specific adaptation process created from the model in (c)



(1) Original design configuration before product adaptation
(2) Adapted design configuration after product adaptation

Figure 4.3. Changes of models for the design of an adaptable product

The following rules should be satisfied for modelling design nodes in the generic product AND-OR tree:

- For an unadaptable super-node, when its sub-nodes are associated with an AND relation, at least one of its sub-nodes should be unadaptable.
- For an unadaptable super-node, when its sub-nodes are associated with an OR relation, all the sub-nodes should be unadaptable.
- For an adaptable super-node, when its sub-nodes are associated with an AND relation or an OR relation, all the sub-nodes should be adaptable.
- For an adaptable super-node, when its sub-nodes are associated with an OR-A relation, all the sub-nodes should be adaptable for different product configurations, considering product adaptation.
- For nodes in a module, all the nodes should be either unadaptable or adaptable. Only AND relations are used to associate sub-nodes in a module.

(b) Creation of a specific original design configuration with alternative solutions of the adapted design configurations and the adaptation processes

Specific original design configuration candidates are created from the generic product design AND-OR tree through tree-based search. A specific original design configuration with alternative solutions of the adapted design configurations and the adaptation processes is defined by an AND-OR tree. Figure 4.3(b) shows a specific original design configuration created from the AND-OR tree given in Figure 4.3(a). The following rules are used to generate a specific original design configuration:

- First, select the root node (e.g., Node D).
- If the selected node has sub-nodes associated with an AND relation (e.g., Node D, Node P5), all these sub-nodes should be selected.
- If the selected node is an unadaptable design node and its sub-nodes are associated with an OR relation (e.g., Node B), only one sub-node should be selected.

- If the selected node is an adaptable design node and its sub-nodes are associated with an OR-A relation (e.g., Node A1, Node C5), all the sub-nodes should be selected.
- If the selected node is an adaptable design node for the original design configuration and its sub-nodes are associated with an OR relation (e.g., Node A2), only one sub-node should be selected.
- If the selected node is an adaptable design node for the adapted design configuration and its sub-nodes are associated with an OR relation (e.g., Node A3), all the sub-nodes should be selected.
- If the selected node is a process node and its sub-nodes are associated with an OR relation (e.g., Node P4), all the sub-nodes should be selected.

(c) Creation of a solution with a specific original design configuration, a specific adapted design configuration, and alternative adaptation processes

Specific adapted design configuration candidates are created from the specific original design configuration AND-OR tree through tree-based search. A solution with a specific original design configuration, a specific adapted design configuration, and alternative adaptation processes is defined by an AND-OR tree. Figure 4.3(c) shows a solution with a specific original design configuration, a specific adapted design configuration, and alternative adaptation processes created from the AND-OR tree given in Figure 4.3(b). The following rules are used to generate a solution with a specific original design configuration, a specific adapted design configuration, and alternative adaptation processes:

- First, select the root node (e.g., Node D).
- If the selected node has sub-nodes associated with an AND relation (e.g., Node D, Node P5), all these sub-nodes should be selected.
- If the selected node is an adaptable design node and its sub-nodes are associated with an OR-A relation (e.g., Node A1, Node C5), all the sub-nodes should be selected.
- If the selected node is an adaptable design node for the adapted design configuration and its sub-nodes are associated with an OR relation (e.g., Node A3), only one sub-node should be selected.

- If the selected node is a process node and its sub-nodes are associated with an OR relation (e.g., Node P4), all the sub-nodes should be selected.

(d) Creation of a final solution with a specific original design configuration, a specific adapted design configuration, and a specific adaptation process

Specific product adaptation process candidates are created from the specific adapted design configuration AND-OR tree through tree-based search. A final solution with a specific original design configuration, a specific adapted design configuration, and a specific adaptation process is defined by an AND-OR tree. Figure 4.3(d) shows a final solution created from the AND-OR tree given in Figure 4.3(c). The following rules are used to generate a final solution:

- First, select the root node (e.g., Node D).
- If the selected node has sub-nodes associated with an AND relation (e.g., Node D, Node P5), all these sub-nodes should be selected.
- If the selected node is an adaptable design node and its sub-nodes are associated with an OR-A relation (e.g., Node A1, Node C5), all the sub-nodes should be selected.
- If the selected node is a process node and its sub-nodes are associated with an OR relation (e.g., Node P4), only one sub-node should be selected.

From a final solution for adaptable product design, multiple product configurations are created considering product adaptation. In this work, only two configurations, i.e., the original product configuration before product adaptation and the adapted product configuration after product adaptation, are considered. Figure 4.4 shows configuration of the original design, configuration of the adapted design, and process of product adaptation created from the AND-OR tree given in Figure 4.3(d).

The following rules are used to create product configurations before and after the product adaptation process:

- First, select the root node (e.g., Node D).
- If the selected node has sub-nodes associated with an AND relation (e.g., Node D, Node P5), all these sub-nodes should be selected.

- Process nodes are selected only for the tree of the adapted design.
- If the selected node is an adaptable design node and its sub-nodes are associated with an OR-A relation (e.g., Node A1, Node C5), only one sub-node should be selected for the original design configuration or the adapted design configuration.

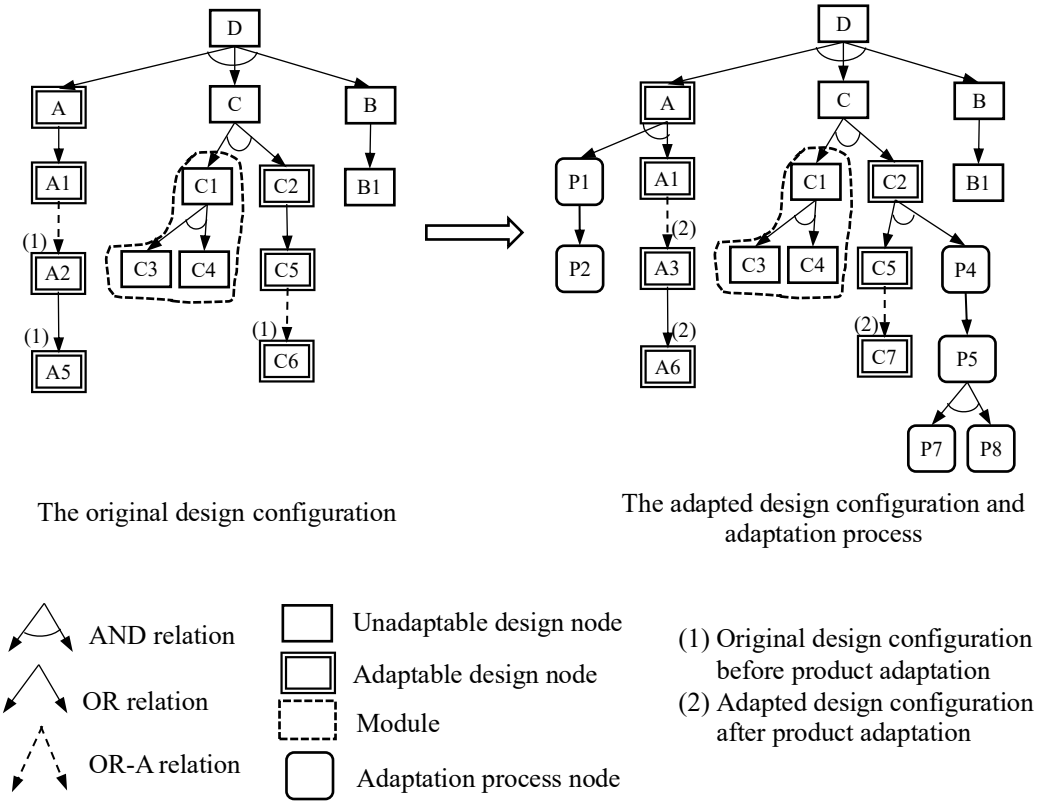


Figure 4.4. The original design configuration, the adapted design configuration and the adaptation process

4.2.2.2. Evaluation for the design of adaptable products

A solution S_i $(i = 1, 2, \dots, p)$ with a specific original design configuration, a specific adapted design configuration, and a specific adaptation process is further defined by its parameters $\boldsymbol{X_i}$ including parameters for the original design configuration $\boldsymbol{X_i^{(OD)}}$, parameters for the adapted design configuration $\boldsymbol{X_i^{(AD)}}$, and parameters for the adaptation process $\boldsymbol{X_i^{(AP)}}$. Some parameters are shared in $\boldsymbol{X_i^{(OD)}}$, $\boldsymbol{X_i^{(AD)}}$ and $\boldsymbol{X_i^{(AP)}}$.

$$\boldsymbol{X_i} = \left\{\boldsymbol{X_i^{(OD)}}, \boldsymbol{X_i^{(AD)}}, \boldsymbol{X_i^{(AP)}}\right\}, \quad i = 1, 2, \dots, p \tag{4.1}$$

In this research, m evaluation measures, such as performance and cost, are used to evaluate a feasible solution, S_i $(i = 1, 2, \dots, p)$, which is defined by its design and process parameters $\boldsymbol{X_i}$.

$$F_j = f_j(\boldsymbol{X_i}),\ i = 1, 2, \dots, p;\ j = 1, 2, \dots, m \tag{4.2}$$

where F_j represents the *j-th* evaluation measure. When the same evaluation measure is calculated by different functions for the original design configuration and the adapted design configuration (e.g., the reliability for the ICE configuration and the EV configuration of the car), this evaluation measure can be achieved by:

$$F_j = f_j(\boldsymbol{X_i}) = \frac{\alpha_j^{(OD)} f_j^{(OD)}(\boldsymbol{X_i}) + \alpha_j^{(AD)} f_j^{(AD)}(\boldsymbol{X_i})}{\alpha_j^{(OD)} + \alpha_j^{(AD)}},\ i = 1, 2, \dots, p;\ j = 1, 2, \dots, m \tag{4.3}$$

where $f_j^{(OD)}(\boldsymbol{X_i})$ and $f_j^{(AD)}(\boldsymbol{X_i})$ are the functions to calculate the evaluation measures for the original design configuration and the adapted design configuration, and $\alpha_j^{(OD)}$ and $\alpha_j^{(AD)}$ are the weighting factors for the original design configuration and the adapted design configuration considering the *j-th* evaluation measure. For the adaptable vehicle, the operation durations $T^{(OD)}$ and $T^{(AD)}$ for the two configurations can be used as the weighting factors for the ICE configuration and the EV configuration of the car.

The different evaluation measures are usually defined by different units such as efficiency and cost. To consider all these measures for evaluation of a design solution, these evaluation measures are first converted into comparable evaluation indices between 0 and 1, representing satisfaction levels in these evaluation aspects.

$$I_j(\boldsymbol{X_i}) = g_j(F_j) = g_j\left(f_j(\boldsymbol{X_i})\right),\ i = 1, 2, \dots, p;\ j = 1, 2, \dots, m \tag{4.4}$$

where $g_j()$ is the numerical function to obtain $I_j(\boldsymbol{X_i})$, and $I_j(\boldsymbol{X_i})$ is the evaluation index of the *j-th* evaluation measure.

In this research, similar to Chapter 3, the method developed by Yang et al. (2006) is used to convert evaluation measures into evaluation indices. In this method, the evaluation indices (i.e., satisfaction levels) for different evaluation measures are collected from customers and/or engineers as data points. A linear or a non-linear relationship between the evaluation measure and the

evaluation index is then defined by a polynomial function. The least-squares curve-fitting method is subsequently used to obtain the coefficients of the polynomial function.

The overall evaluation index, $I(\boldsymbol{X_i})$, considering all evaluation aspects is defined by:

$$I(\boldsymbol{X_i}) = \frac{\sum_{j=1}^{m}\left(W_j I_j(\boldsymbol{X_i})\right)}{\sum_{j=1}^{m} W_j} \tag{4.5}$$

where W_j represents the weighting factor of the *j-th* evaluation index.

4.2.2.3. Optimization for the design of adaptable products

The optimal solution with the original design configuration, the adapted design configuration, the product adaptation process, and the parameters of configurations and process is obtained through the multi-level optimization method (Xue 1997).

- *Parameter optimization*

  For a solution with the original design configuration, the adapted design configuration, and the product adaptation process, parameter optimization is conducted to obtain the optimal values of these parameters and the optimal evaluation index corresponding to these optimal parameter values.

- *Configuration/process optimization*

  Each solution defined by its original design configuration, adapted design configuration, and product adaptation process is evaluated by its optimal evaluation index obtained through parameter optimization. Among all the solutions, the optimal one is achieved through configuration/process optimization.

Parameter optimization for a solution S_i $(i = 1, 2, \dots, p)$ with its original design configuration, the adapted design configuration, and the product adaptation process is defined by:

$$\max_{w.r.t.\ \boldsymbol{X_i}} I(\boldsymbol{X_i}) \tag{4.6}$$

s.t.

$$\boldsymbol{X_i}^{(L)} \leq \boldsymbol{X_i} \leq \boldsymbol{X_i}^{(U)}$$

where $\boldsymbol{X_i}$ represents the vector of parameter variables, $I(\boldsymbol{X_i})$ is the optimization objective function to be maximized, and $\boldsymbol{X_i}^{(L)}$ and $\boldsymbol{X_i}^{(U)}$ are the lower bounds and upper bounds of $\boldsymbol{X_i}$, respectively. The bounds of the variable parameters are determined based on factors such as physical and manufacturing constraints to ensure feasible solutions. Equality constraints and inequality constraints can also be considered in parameter optimization. When the parameters are defined by discrete values or the evaluation measures in the whole parameter space need to be calculated, the exhaustive method is used for parameter optimization. When the design parameters are defined by continuous values, numerical search (Rao 2009) is employed for parameter optimization.

Among all the candidate solutions, the optimal one is achieved by configuration/process optimization defined by:

$$\max_{w.r.t.\ S_i} I(\boldsymbol{X_i^*}) \tag{4.7}$$

where $\boldsymbol{X_i^*}$ is the vector of the optimal parameter values for the *i-th* solution candidate S_i, and $I(\boldsymbol{X_i^*})$ is the corresponding optimal evaluation index. Exhaustive method is used for the configuration/process optimization when the number of solutions is not large. However, when the number of solutions is considerably large, genetic programming (Rao 2009) is employed for the configuration/process optimization. The effectiveness of genetic programming for optimization with solutions modelled by AND-OR trees was demonstrated in the previous research on configuration optimization (Hong et al. 2008).

4.3. A Case Study: Design of an Adaptable Vehicle for Easy Conversion from the ICE Configuration to the EV Configuration

The developed method was used for design of an adaptable vehicle for easy conversion from its ICE configuration to its EV configuration.

4.3.1. Problem for the design of the adaptable vehicle

Conversion of an ICE car into an EV car, as shown in Figure 4.5, typically starts with the removal of the ICE components, including the engine, fuel tank, and exhaust system. An electric motor capable of providing the desired power and torque is then selected and installed. A battery pack, which is usually composed of battery cells connected in series and/or parallel to satisfy power

and voltage requirements for the electric motor, and other modules are subsequently selected and installed.

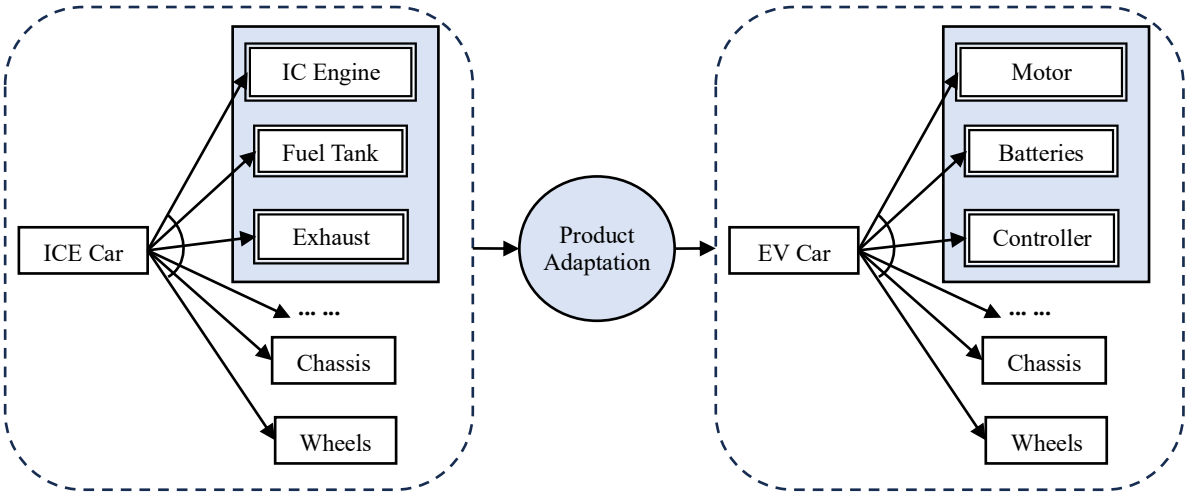


Figure 4.5. Product conversion from the ICE car to the EV car

Instructions, parts, and services for the conversion of ICE cars to EV cars are provided by many companies and websites (Toms 2021). An optimization method was developed in Chapter 3 to identify the best adapted design and adaptation process for product adaptation, and this method was used to achieve the optimal adapted design configuration, product adaptation process, and parameter values of the design configuration and the adaptation process for conversion of an existing ICE car to an EV car. The case study presented in this section aims to further improve the effectiveness of the adaptable product design approach by developing a new adaptable vehicle for easy product adaptation from its ICE configuration to its EV configuration.

4.3.2. Modelling for the design of the adaptable vehicle

The generic adaptable vehicle, considering all possible ICE configurations, EV configurations, and processes to convert from ICE configurations to EV configurations, is shown in Figure 4.6. Design nodes and process nodes are associated with design and process parameters. In this work, the 2022 Toyota Camry was selected as the baseline model. Information from (Toms 2021) was used for the modelling of product adaptation from the ICE configuration to the EV configuration. The major alternative solutions for the original design configuration, the adapted design configuration, and the adaptation process are summarized in Table 4.1. In this case study, only the major decision-making issues for the adaptable vehicle design were considered.

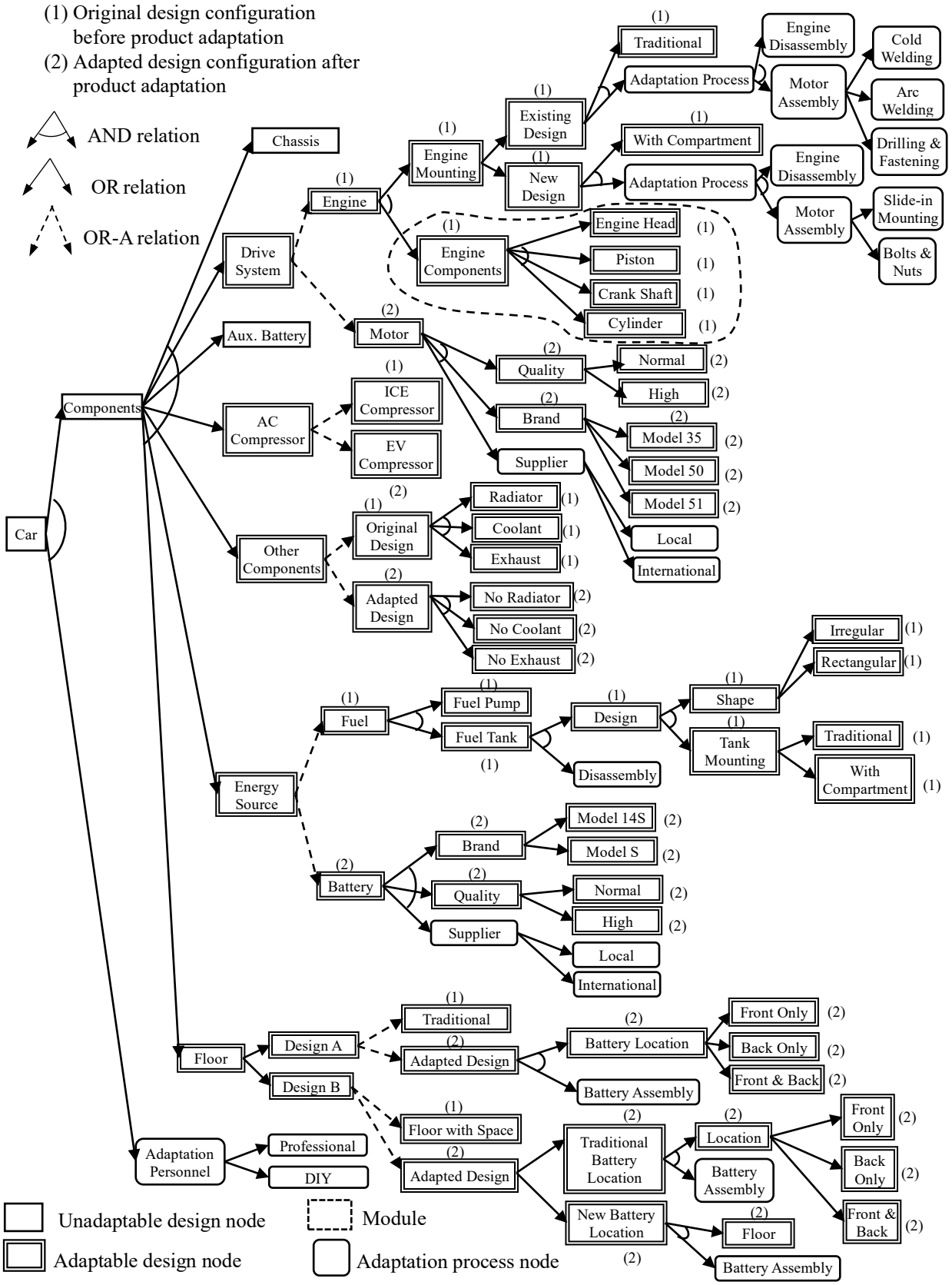


Figure 4.6. The generic product AND-OR tree for design of an adaptable vehicle

Table 4.1. Alternative solutions for the original design configuration, the adapted design configuration and the adaptation process

Aspect	Item	Alternatives
Original design configuration (i.e., ICE configuration)	Engine mounting	• Existing design with traditional mounting only for engine • New design with a compartment for easy mounting of engine, motor and batteries
	Shape of fuel tank	• Irregular shape with the optimal space utilization for fuel • Rectangular shape for both fuel and batteries
	Fuel tank mounting	• Existing design with traditional mounting only for fuel tank • New design with a compartment for easy mounting of fuel tank and batteries
	Floor	• Traditional design with a single layer • New design with two layers and space between two layers
Adapted design configuration (i.e., EV configuration)	Quality of motor	• Normal quality in reliability • High quality in reliability
	Series of motor	• Model 35 series • Model 50 series • Model 51 series
	Quality of batteries	• Normal quality in reliability • High quality in reliability
	Series of batteries	• Model 14S series • Model S series
	Location of batteries	*For traditional floor design with single layer* • Front hood only • Back fuel position only • Front hood and back fuel position *For new floor design with two layers and space between them* • Front hood only • Back fuel position only • Front hood and back fuel position • Space in floor
Adaptation process (i.e., conversion process)	Motor assembly	*For traditional engine mounting design without compartment* • Cold welding • Arc welding • Drilling and fastening *For new engine mounting design with compartment* • Slide-in mounting • Bolts and nuts
	Supplier of motor	• Local • International
	Supplier of batteries	• Local • International
	Personnel	• Professional mechanic • Hobby customer as DIY project

From this AND-OR tree, candidate solutions of the ICE configurations, EV configurations, and conversion processes were created using the methods given in Section 4.2.2.1 through tree-based search. For this case study, a total of 26,880 solutions were created, and each solution was defined by a tree representing its ICE configuration, EV configuration and conversion process.

Various databases were defined to model the available components (e.g., motors and batteries) at different suppliers, and specifications of these components. Table 4.2 shows the database for available motors from an international supplier.

Table 4.2. Available motors in an international supplier

ID	Series	Power (hp)	Quality	Cost ($)
M1	Model-35	60	Normal	2000
M2	Model-35	60	High	2500
M3	Model-35	80	High	3000
…	…	…	…	…
M19	Model-51	200	Normal	12000
M20	Model-51	200	High	12500

A solution with its ICE configuration, EV configuration, and conversion process is defined by a tree. Since nodes of this tree are associated with parameters for the original design configuration, the adapted design configuration, and the adaptation process, a solution S_i $(i = 1, 2, \dots, 26{,}880)$ can be defined by these parameters as shown in Equation (4.1). In this case study, only two major parameters for the adapted design configuration were selected as variables for parameter optimization.

(1) *P*: Power of the electric motor (*hp*)

(2) *N*: Number of the batteries (*integer*)

A solution S_i in this case study can be defined by its parameters as:

$$\boldsymbol{X_i} = (P_i, N_i), \quad i = 1, 2, \dots, 26{,}880 \tag{4.8}$$

The two design parameters were selected as variables based on the following considerations:

- Among the influences of factors considering different design configurations and different design parameter values on evaluation measures, the selection of different design

configurations plays a dominating role in achieving the optimal evaluation measures compared with the selection of different design parameter values.

- Among all the design parameters, only some parameters influence the selected evaluation measures and tradeoffs among these evaluation measures. For parameters exhibiting monotonic increasing or decreasing relationships with single evaluation measures, values of these parameters are usually selected at their boundaries defined by constraints.

4.3.3. Evaluation for the design of the adaptable vehicle

In this study, five measures were selected for evaluation of a solution with its parameters.

- C: Total cost for ICE configuration, EV configuration, and conversion process (*$*)
- D: Total duration for conversion process (*days*)
- A: Acceleration time of the EV from a stationary position to a normal speed (*seconds*)
- R: Reliability of EV for 5 years (*%*)
- B: Balance of weights for the EV ($N{\cdot}m$)

(1) Total cost: C ($)

The total cost C was obtained by:

$$C = C_{OD} + C_{AD} + C_{AP} \tag{4.9}$$

where C_{OD} is the cost of components for the original design configuration (i.e., ICE configuration), C_{AD} is the extra cost of components for the adapted design configuration (i.e., EV configuration), and C_{AP} is the cost for the adaptation process (i.e., conversion).

- The cost for the original design configuration C_{OD} was calculated from the costs of components and tasks to build the ICE configuration, including engine, ICE compressor, fuel tank, fuel pump, chassis, floor, engine mounting, fuel tank mounting, etc.
- The extra cost for the adapted design configuration C_{AD} was calculated from the extra costs of components to build the EV configuration, including motor, battery pack, EV compressor, etc.

- The cost for the product adaptation C_{AP} was calculated from the costs of activities for the conversion process, including disassembly of engine, disassembly of fuel tank, delivery of motor, delivery of battery units, assembly of motor, assembly of battery units, etc.

(2) Total duration for conversion process: D (days)

The total duration D for conversion from the ICE configuration to the EV configuration was calculated by:

$$D = max\{D_{MD}, D_{BD}\} + D_{PD} \tag{4.10}$$

where D_{MD} is the duration for motor delivery, D_{BD} is the duration for battery units delivery, and D_{PD} is the duration of product adaptation by the personnel. The conversion process was started after all the components of the EV configuration had been delivered. Delivery times of the components were influenced by the locations of suppliers and delivery methods. The duration of the conversion was influenced by the schedules and skills of the personnel for the conversion tasks.

(3) Acceleration time of the EV from a stationary position to normal speed: A (seconds)

The acceleration time A for the EV to start from a stationary position with a speed of 0 km/hour to the normal driving speed of 60 km/hour was obtained by:

$$A = \frac{M\left(v \times \frac{1000}{3600}\right)^2}{2 \times (746\ P)} \tag{4.11}$$

where M is the total mass of the EV (kg), v is the normal driving speed of 60 km/hour, and P is the power of the selected motor (hp). The total mass M was influenced by the weight of the battery unit and the number of battery units N. P and N were design variables for parameter optimization.

(4) Reliability of EV for 5 years: R (%)

The reliability of EV for 5 years, considering the reliabilities of the two major EV components, the motor and the batteries, was calculated by:

$$R = R_M \times (R_B)^N \tag{4.12}$$

where R_M *(%)* and R_B *(%)* are the reliability of the selected motor and the reliability of the selected battery unit, respectively, and N is the number of battery units. In this work, the probability that a module would not fail within 5 years was selected as the reliability measure. Reliability measures of motor and battery units were influenced by quality specifications of these components.

(5) Balance of weights for the EV: B (N·m)

Balance of weights for the EV, *B (N·m),* was defined by the balances considering the motor and battery pack.

$$B = |\sum_i B_i| = |\sum_i (M_i g Y_i)|, \;\; i = motor, battery\ unit \tag{4.13}$$

where M_i is the mass of the component (kg), g is the acceleration due to gravity ($g = 9.81\ m/s^2$), and Y_i is the distance from the center of the component's weight to the center of the EV (m). In this work, only the balance in the direction perpendicular to the driving direction was considered. The weight balance B can also be considered as the total torque due to forces of the motor and battery units applied to the center of the EV due to its acceleration with value g when the car is turned in the driving direction. In this case study, the motor was mounted in the front hood. The battery units were mounted with four options: only in the front hood, only in the back fuel position, both in the front hood and the back fuel position, and in the space between the two floor layers. Y_i is positive when the weight is in the front position of the EV, while Y_i is negative when the weight is in the back position of the EV.

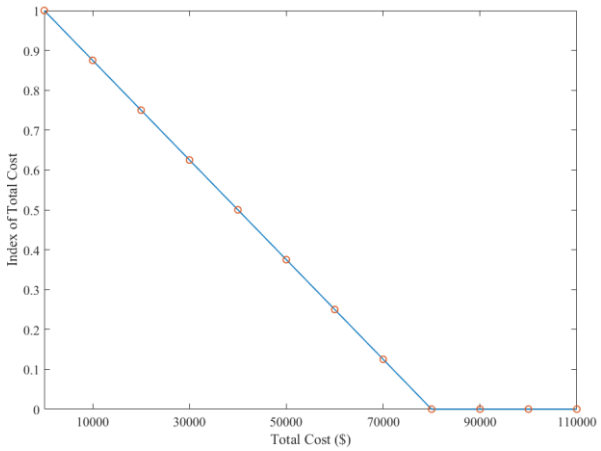
Since the five evaluation measures in this case study were in different units, these evaluation measures were converted into comparable evaluation indices using the method explained in Equation (4.4). Figure 4.7 shows the data points and the fitted polynomial curves to model the relations between the five evaluation measures and their corresponding evaluation indices.

All the evaluation indices and their corresponding weighting factors were integrated into an overall evaluation index I, which was defined by:

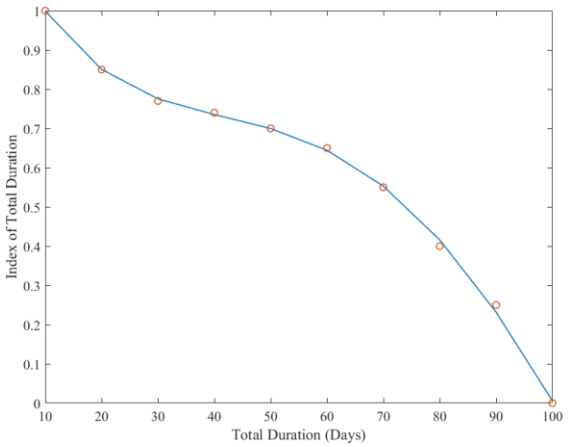
$$I = \frac{W_C I_C + W_D I_D + W_A I_A + I_R W_R + W_B I_B}{W_C + W_D + W_A + W_R + W_B} \tag{4.14}$$

where the weighting factors for these five evaluation indices were selected as:

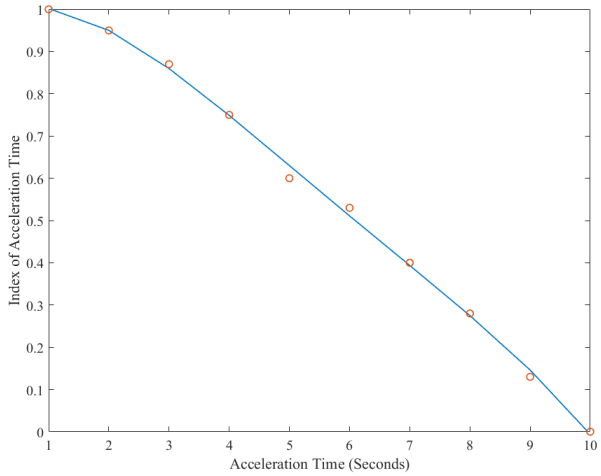
$W_C = 0.8$, $W_D = 0.2$, $W_A = 0.4$, $W_R = 0.2$, and $W_{\mathrm{B}} = 0.1$



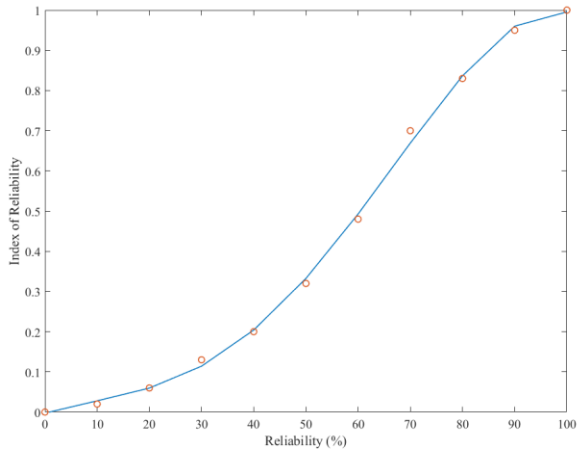
(a). Total cost and its index



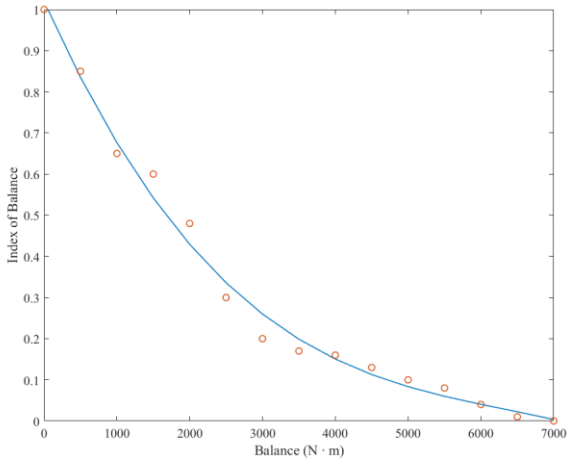
(b). Total duration and its index



(c). Acceleration time and its index



(d). Reliability and its index



(e). Balance and its index

Figure 4.7. Relations between five evaluation measures and their evaluation indices

4.3.4. Optimization for the design of the adaptable vehicle

The optimal configuration/process solution and its corresponding optimal parameter values were obtained using the multi-level optimization method introduced by Xue (1997). First, 26,880 configuration/process solutions S_i $(i = 1, 2, \dots, 26{,}880)$ were created from the AND-OR tree given in Figure 4.6 through tree-based search. Each of these 26,880 configuration/process solutions was defined by a tree representing its ICE configuration, EV configuration, and conversion process. For each configuration/process solution S_i, parameter optimization was conducted to obtain the optimal values of the two selected design variables *P* and *N* for this solution by:

$$\max_{w.r.t.(P,N)} I_i = I_i(P, N), \quad i = 1, 2, \dots, 26{,}880 \tag{4.15}$$

$$s.t.$$

$$60 \le P \le 180$$

$$10 \le N \le 30$$

where the evaluation index defined by Equation (4.14) for the S_i configuration/process solution was selected as the optimization objective function.

Among the 26,880 configuration/process solutions, the optimal one was achieved by configuration/process optimization.

$$\max_{w.r.t.\ S_i} I_i^* = I_i(P_i^*, N_i^*) \tag{4.16}$$

where P_i^* and N_i^* are the optimal values achieved through parameter optimization for the S_i configuration/process solution, and I_i^* is the optimal evaluation index corresponding to the optimal parameter values for the *i-th* configuration/process solution.

To avoid the optimal solution falling into local optimal points, the exhaustive method was used for the multi-level optimization to find the true optimal solution. For configuration/process optimization, all the 26,880 configuration/process solutions were created through tree-based search, and the best one was selected as the final configuration/process solution. For parameter optimization, since the number of batteries, *N*, in Equation (4.15) was an integer between 10 and 30, all the integers between 10 and 30 were considered for parameter optimization. The power of

the electric motor, *P*, in Equation (4.15) was a real number between 60 hp and 180 hp. In the iteration process for parameter optimization, the current value of *P* was used to check with the relevant database (e.g., the available motors in an international supplier, given in Table 4.2). The nominal power of the selected motor with the closest value to the current value of *P* was selected as the current optimization result to evaluate the optimization objective function. MATLAB was used for implementation of the multi-level optimization method.

The true optimal solution was achieved as:

- **The ICE configuration**

  Engine Mounting = Compartment, Fuel Tank Shape = Rectangular, Fuel Tank Mounting = Traditional, Floor Type = Floor with Space

- **The EV configuration**

  Motor Quality = High, Motor Brand = Model 50, Battery Brand = Model 14S, Battery Quality = High, Battery Location = Floor

- **The conversion process**

  Motor Assembly = Bolts and Nuts, Motor Supplier = International, Battery Supplier = International, Adaptation Personnel = DIY

- **The parameter values**

  P = 146 hp, N= 16 batteries

The evaluation measures and their evaluation indices corresponding to the optimal solution are shown in Table 4.3.

Table 4.3. Evaluation measures and evaluation indices for the optimal solution

Evaluation measure	Optimal value	Optimal index
Total cost: *C ($)*	43,940	0. 6005
Total duration: *D (days)*	35	0.7530
Acceleration time: *A (s)*	2.480	0.9101
Reliability: *R (%)*	70.93	0.6857
Balance *B: (N · m)*	465.0	0.8471
Overall evaluation index: *I*		**0. 7158**

4.3.5. Comparison between the adaptable vehicle and the traditional vehicle

The adaptable vehicle was compared with the traditional vehicle, considering product adaptation as shown in Table 4.4.

Table 4.4. Comparison between the traditional vehicle and the adaptable vehicle

Aspect	Item	Traditional Vehicle	Adaptable Vehicle	Improvement
ICE Configuration	Engine Mounting	Traditional	Compartment	
	Fuel Tank Shape	Irregular	Rectangular	
	Fuel Tank Mounting	Traditional	Traditional	
	Floor Type	Traditional Floor	Floor With Space	
EV Configuration	Motor Quality	High	High	
	Motor Brand	Model 50	Model 50	
	Battery Brand	Model 14S	Model 14S	
	Battery Quality	High	High	
	Battery Location	Back	Floor	
Conversion Process	Motor Assembly	Drilling and Fastening	Bolts and Nuts	
	Motor Supplier	International	International	
	Battery Supplier	International	International	
	Adaptation Personnel	DIY	DIY	
Optimal Parameters	Power: P *(hp)*	146	146	
	Number of Batteries: N	16	16	
Evaluation Measures	Total Cost: C *($)*	47,170	43,940	+6.850 %
	Total Duration: D *(Days)*	70	35	+50.00 %
	Acceleration Time: A *(s)*	2.482	2.482	0.000 %
	Reliability: R *(%)*	70.93	70.93	0.000 %
	Balance: B *($N \cdot m$)*	3127	465.0	+85.13 %
Evaluation Indices	Total Cost Index: I_C	0.5712	0.6005	+5.130 %
	Total Duration Index: I_D	0.5528	0.7530	+36.21 %
	Acceleration Time Index: I_A	0.9101	0.9101	0.000 %
	Reliability Index: I_R	0.6857	0.6857	0.000 %
	Balance Index: I_B	0.2429	0.8471	+248.7 %
Overall	Overall Evaluation Index: I	0.6429	0.7158	+11.28 %

- **Adaptation of the traditional vehicle (i.e., the existing vehicle)**

  The components of the original ICE configuration for the traditional vehicle were selected manually based on the existing vehicle. The adapted EV configuration, the conversion process, and the parameter values of the traditional vehicle were achieved by the multi-level optimization method.

- **Adaptation of the new adaptable vehicle**

  The original ICE configuration, the adapted EV configuration, the conversion process, and the parameter values of the adaptable vehicle were achieved by the multi-level optimization method. The adaptable vehicle in Table 4.4 is the same as the one achieved in Section 4.3.4.

The overall evaluation index defined by Equation (4.14) was used as the optimization objective function for the multi-level optimization. The optimal solutions of the adaptable vehicle and the traditional vehicle, and their evaluation measures and evaluation indices are shown in Table 4.4. Compared with the traditional vehicle, the total cost was reduced, the total duration for adaptation was shortened, and the balance was improved by the new adaptable vehicle.

The comparison results considering only costs are shown in Table 4.5. From this table, we can see that although the cost of the ICE configuration for the adaptable vehicle is higher than the cost of the traditional vehicle, the cost of the conversion process for the adaptable vehicle is much lower, thus leading to the reduction of the total cost.

Table 4.5. Comparison between the traditional vehicle and the adaptable vehicle considering costs

Cost Item	Traditional Vehicle	Adaptable Vehicle	Cost Difference ($)	Improvement (%)
Cost for ICE Configuration: C_{OD} *($)*	22,810	24,010	-1,200	-5.260 %
Extra Cost for EV Configuration: C_{AD} *($)*	14,950	14,950	0.000	0.000 %
Cost for Conversion: C_{AP} *($)*	9,410	4,980	4,430	+47.08 %
Total cost: *C ($)*	47,170	43,940	3,230	+6.85 %

4.3.6. Comparative study for the optimal design of adaptable vehicles considering different weighting factors of the evaluation aspects

In this comparative study, five additional cases with different design requirements defined by different weighting factors were considered. For each of these five cases, one of the weighting factors was selected as 1.0, while all other weighting factors were reduced to 1% of their original values. The optimization objective function in Equation (4.14) was defined using these weighting factors. The optimization results are shown in Table 4.6.

Table 4.6. Comparison among different adaptable vehicles created considering different weighting factors in the requirements

Aspect	Item	Adaptable Vehicle	Case 1	Case 2	Case 3	Case 4	Case 5
Design Requirements	Weights for Evaluation Indices	W_C=0.8 W_D=0.2 W_A=0.4 W_R=0.2 W_B=0.1	W_C=1.0 W_D=0.002 W_A=0.004 W_R=0.002 W_B=0.001	W_C=0.008 W_D=1.0 W_A=0.004 W_R=0.002 W_B=0.001	W_C=0.008 W_D=0.002 W_A=1.0 W_R=0.002 W_B=0.001	W_C=0.008 W_D=0.002 W_A=0.004 W_R=1.0 W_B=0.001	W_C=0.008 W_D=0.002 W_A=0.004 W_R=0.002 W_B=1.0
ICE Configuration	Engine Mounting	Compartment	Compartment	Compartment	Compartment	Compartment	Compartment
	Fuel Tank Shape	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular
	Fuel Tank Mounting	Traditional	Traditional	Traditional	Traditional	Traditional	Traditional
	Floor Type	Floor With Space	Floor With Space	Floor With Space	Floor With Space	Floor With Space	Floor With Space
EV Configuration	Motor Quality	High	Normal	High	High	High	High
	Motor Brand	Model 50	Model 35	Model 50	Model 51	Model 50	Model 50
	Battery Brand	Model 14S	Model 14S	Model 14S	Model 14S	Model 14S	Model 14S
	Battery Quality	High	Normal	High	High	High	High
	Battery Location	Floor	Floor	Floor	Floor	Floor	Floor
Conversion Process	Motor Assembly	Bolts and Nuts	Bolts and Nuts	Bolts and Nuts	Bolts and Nuts	Bolts and Nuts	Bolts and Nuts
	Motor Supplier	International	International	Local	International	International	International
	Battery Supplier	International	International	Local	International	International	International
	Adaptation Personnel	DIY	DIY	Professional	DIY	DIY	DIY
Optimal Parameters	Power P	146	60	143	180	146	146
	Number of batteries N	16	17	16	16	10	10
Evaluation Measures	Total Cost ($)	43,940	36,530	56,280	47,140	54,227	54,227
	Total Duration (Days)	35	35	20	35	35	35
	Acceleration Time (s)	2.482	6.210	2.260	2.070	2.480	2.480
	Reliability (%)	70.93	38.89	70.93	70.93	80.07	80.07
	Balance (N · m)	465.0	456.4	465.0	465.0	315.4	315.4

From this table, we can see:

- When the total cost was considered important (i.e., Case 1), the motor with the lowest power was selected. The smallest number of batteries was not selected because the cost of a battery cell with a large energy capacity was high.
- When the total duration of adaptation was considered important (i.e., Case 2), the local suppliers for motor and batteries were selected. A professional mechanic was also selected for the conversion.
- When the acceleration time of the EV was considered important (i.e., Case 3), the motor with the highest power was selected.
- When the reliability was considered important (i.e., Case 4), the motor and batteries with high quality were selected.
- When the balance of weights was considered important (i.e., Case 5), the minimum number of batteries was selected.

4.4. Summary

In this research, a new method was developed to identify the original design configuration, the adapted design configuration, and adaptation process for the design of an adaptable product. In this method, the generic adaptable product design considering alternative solutions of the original design configurations, the adapted design configurations, and the product adaptation processes was modelled by an AND-OR tree. All feasible solutions consisting of the original design configurations, the adapted design configurations, and the adaptation processes were created through tree-based search. The feasible solutions were then evaluated using multiple evaluation measures. The multiple evaluation measures with different units were converted into comparable indices and then integrated into an overall evaluation index for optimization. Two-level optimization (i.e., configuration/process optimization and parameter optimization) was conducted to obtain the optimal original product design configuration, the optimal adapted product design configuration, the optimal adaptation process, and the optimal configuration/process parameter values. This new method was employed for the design of an adaptable vehicle for easy conversion from its ICE configuration to its EV configuration.

The following conclusions have been obtained through this research.

(1) Compared with our previously developed method for optimal adaptation of an existing product explained in Chapter 3, the new method for design of new adaptable product can reduce the overall efforts in product adaptation, thus improving customer satisfaction of the developed product.

(2) The new method is effective for modelling of the adaptable product including its original product configuration, adapted product configuration, product adaptation process, and parameters of the configuration and process, for evaluation of the different design solutions considering multiple evaluation measures with different units, and for optimization to achieve the optimal original design configuration, adapted design configuration, adaptation process, and configuration/process parameters.

(3) The case study has demonstrated potential to develop adaptable vehicles that can be easily converted from their ICE configurations to their EV configurations to better satisfy the government policies on environment.

In Chapters 3 and 4, designs with specific product adaptation requirements were considered. In the next chapter, design of adaptable products considering general product adaptation requirements (i.e., adaptation requirements are not given or unpredictable during the design stage) will be investigated.

Chapter 5. Evaluation of General Product Adaptability for the Design of Adaptable Products

5.1. Introduction

Adaptable products are designed for easy change of their configurations and parameters in the operation stages to satisfy the changes in functional requirements. The design of adaptable products plays an important role in industries in which technologies, consumer preferences, and regulations change frequently.

Design of adaptable products should be evaluated through measures in design. When multiple design candidates are created, the one with the best evaluation measures is selected for production. For the design of adaptable products, the evaluation of product adaptabilities plays a key role in identifying the best design solution from all possible design solution candidates.

As explained in Chapter 1, product adaptation requirements for the design of adaptable products are classified into the following two categories, specific product adaptation requirements and general product adaptation requirements, depending on whether adaptation requirements are given at the design stages.

(1) Specific product adaptation requirements

Specific product adaptation requirements are the ones that are given or can be predicted at the design stage. Adaptable product design considering specific product adaptation requirements can be evaluated by the following methods.

- *Specific product adaptability*

  Specific product adaptability, $A^{(S)}$, was defined in literature by comparing the cost of adaptation tasks to modify an existing product and the cost of creating a new product to satisfy a new functional requirement (Gu et al. 2004). The specific product adaptability is calculated by $A^{(S)} = \frac{C_{(0\rightarrow \text{Adapted})} - C_{(\text{Existing}\rightarrow \text{Adapted})}}{C_{(0\rightarrow \text{Adapted})}}$, where $C_{(0\rightarrow \text{Adapted})}$ and $C_{(\text{Existing}\rightarrow \text{Adapted})}$ are the cost of creating a new product from scratch and the cost of adapting an existing product, respectively. In other words, the specific product adaptability is the ratio between the cost saving achieved by adapting the product instead of creating a new one and the full cost of

creating a new product. When it requires more cost to adapt a product than to develop a new one (i.e., $C_{(\text{Existing}\rightarrow\text{Adapted})} > C_{(0\rightarrow\text{Adapted})}$), product adaptation should not be considered ($A^{(S)} < 0$). When no cost is required for product adaptation (i.e., $C_{(\text{Existing}\rightarrow\text{Adapted})} = 0$), the product is a perfect adaptable product ($A^{(S)} = 1$).

- *Adaptation cost*

  Adaptation cost is the total cost required to convert a product from the original configuration to the adapted configuration. Adaptation cost is calculated by $C_{\text{Adaptation}} = C_{\text{Components}} + C_{\text{Process}}$, where $C_{\text{Components}}$ is the total cost of the components that are added or upgraded to create the adapted design configuration, and C_{Process} is the cost of the adaptation process.

To obtain the best design solution, all the possible design solutions can be evaluated either using the specific product adaptability or the adaptation cost considering the specific adaptation requirements. Either $A^{(S)}$ should be maximized, or $C_{\text{Adaptation}}$ should be minimized. Since $C_{(0\rightarrow\text{Adapted})}$ is a constant for all the possible design solution alternatives, $A^{(S)}$ is maximized when $C_{(\text{Existing}\rightarrow\text{Adapted})}$ is minimized. Therefore, methods with both measures (i.e., $A^{(S)}$ and $C_{\text{Adaptation}}$) are used to rank the design solutions with the same results.

In Chapter 3 and Chapter 4, the evaluation of design solutions for obtaining the best one was carried out based on the adaptation cost.

(2) General product adaptation requirements

General product adaptation requirements are the ones that are unknown or unpredictable at the design stage. In real-world applications, products frequently face unexpected changes in their operating conditions, user needs, or technological advancements during their operation stages. Products should be designed with structures to accommodate for these unpredicted adaptation requirements. General product adaptability is a measure to evaluate product adaptability without specific product adaptation requirements (i.e., with general product adaptation requirements).

The general product adaptability considering relations among different components of the product in the product structure has been introduced in the literature (Fletcher et al. 2009). In this method, the general product adaptability of a product was evaluated by comparing the full architecture of the product, modelled by a graph (i.e., parent-child relations with additional

relations between other nodes), with the segregated architecture of this product, modelled by a tree (i.e., only parent-child relations). The full product architecture and the segregated product architecture are shown in Figure 5.1. The segregated product architecture was considered ideal for adaptable product design since modifying one node did not affect other nodes at the same level. For evaluation of general product adaptability, different types of relations, such as interface relations, interaction relations, functional relations, and physical relations, as well as the relative importance of the nodes (i.e., cost percentages of the components for the product), were also considered.

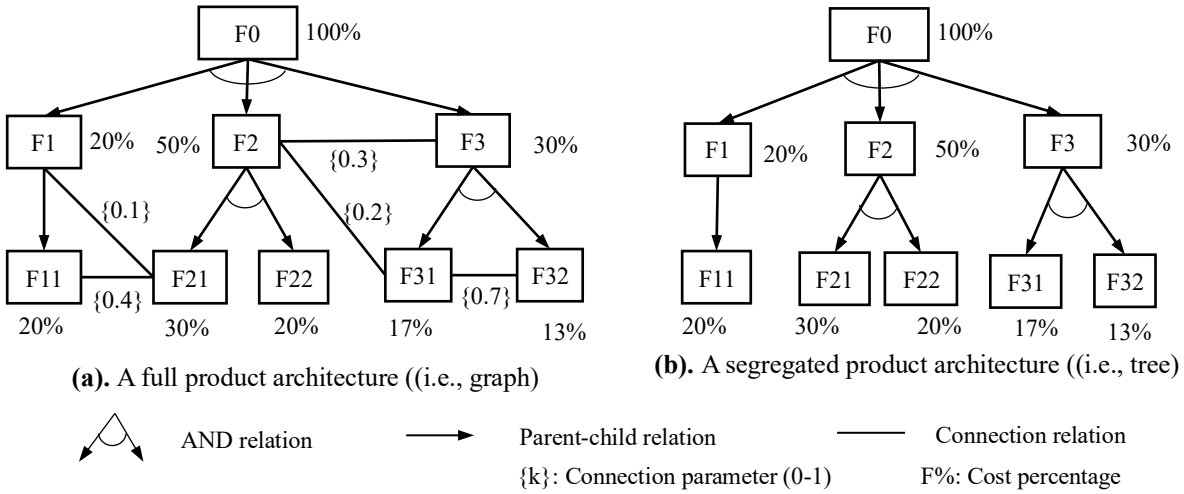


Figure 5.1. Full product architecture and segregated product architecture (modified from Fletcher et al. (2009))

In the work by Fletcher et al. (2009), the impact between a parent node, *i,* and its sub-node, *j*, was modelled by $R_{ij}\left(min\{F_i, F_j\}\right) = min\{F_i, F_j\}$, where R_{ij} was an impact parameter with the value of 1, and F_i and F_j were the importance measures of the two nodes defined by their cost percentages for the whole product. The impact between two nodes that did not have a parent-child relation was modelled by $R_{ij}\left(F_i + F_j\right)$, where R_{ij} was an impact parameter with a value between 0 and 1, considering the influencing factors, including interface relations, interaction relations, functional relations, and physical relations. For a segregated product architecture, the total impact considering parent-child relations was achieved by:

$$k^{(S)} = \sum_{(S)} R_{ij}\left(min\{F_i, F_j\}\right) = \sum_{(S)} min\{F_i, F_j\} \tag{5.1}$$

In a full product architecture, the impact considering the extra relations was described by:

$$k^{(Extra)} = \sum_{(Extra)} R_{ij}\left(F_i + F_j\right) \tag{5.2}$$

The general product adaptability by comparing the full product architecture and its segregated product architecture was achieved by:

$$k = \frac{k^{(S)}}{k^{(S)} + k^{(Extra)}} \tag{5.3}$$

In Chapter 3 and Chapter 4, evaluations were carried out considering only specific product adaptation requirements. Since prediction of specific product adaptation requirements at the design stage is a challenging task, the objective of the research in this Chapter is to extend the previous work to the evaluation of the general product adaptability when specific product adaptation requirements are not given at the design stage.

When the method by Fletcher et al. (2009) is used for the evaluation of general product adaptability based on the modelling scheme developed in the previous research (Martinez and Xue 2018; Saad and Xue 2024; Deabae and Xue 2025), the following factors that influence the measure of general product adaptability must be considered.

(1) Nodes are classified into adaptable nodes and unadaptable nodes, considering whether changes of the components and sub-assemblies are allowed for product adaptation (Saad and Xue 2024).

(2) All the component/sub-assembly nodes in a module must be changed at the same time for product adaptation (Martinez and Xue 2018).

(3) Uncertainties of the component/sub-assembly nodes due to customer preferences, technology advancement, etc. are defined by adaptation probabilities (Deabae and Xue 2025).

To solve the problems summarized above, a new method is developed in this research to evaluate the general product adaptability based on the method developed by Fletcher et al. (2009), considering various influencing factors in our new product modelling scheme, including adaptable and unadaptable components/sub-assemblies, components/sub-assemblies in modules, and uncertainties of components/sub-assemblies in product adaptation. This newly developed method has also been integrated with the previously developed adaptable product design framework, considering cases without or with specific requirements for product adaptations.

5.2. Three Factors That Influence the General Product Adaptability

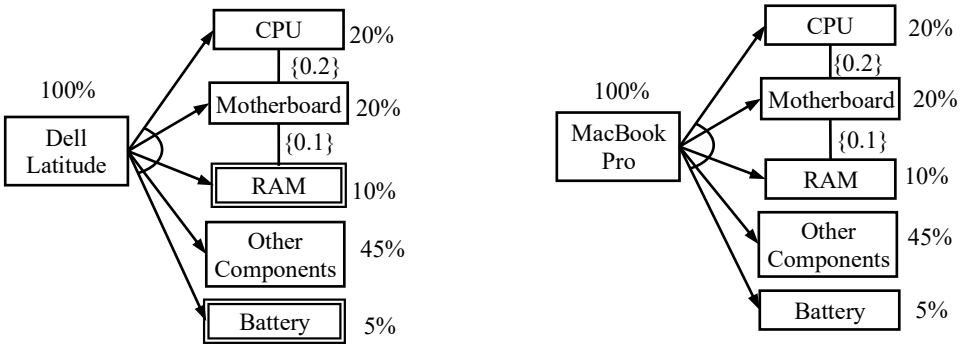
In this research, the method to evaluate the general product adaptability introduced by Fletcher et al. (2009) has been modified by considering the three influencing factors in the new product modelling scheme (Martinez and Xue 2018; Saad and Xue 2024; Deabae and Xue 2025) for the development of the optimal adaptable product design method.

(1) The influence of adaptable and unadaptable components/sub-assemblies

In the method by Fletcher et al. (2009), all the nodes in a graph/tree could be changed. In the real world, however, changes to some components/sub-assemblies are not allowed for product adaptation. For example, the two products shown in Figure 5.2(a) are considered with the same general product adaptability according to the method by Fletcher et al. (2009) because of the same tree/graph structures. However, since the RAM and battery in the Dell Latitude laptop can be upgraded or replaced, while the RAM and battery in the MacBook Pro laptop are integrated into the motherboard and cannot be changed, the Dell Latitude laptop should have better general product adaptability. In this work, design nodes are classified into adaptable nodes and unadaptable nodes, considering whether they can be changed for product adaptation.

(2) The influence of components/sub-assemblies in modules

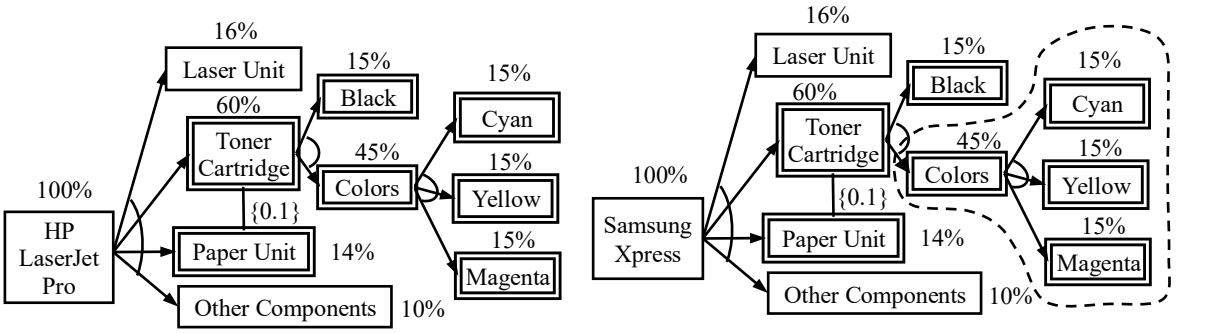
In the method by Fletcher et al. (2009), all the design nodes could be changed separately. In the real world, however, some components/sub-assemblies cannot be separated from each other. For example, the two products shown in Figure 5.2(b) are considered with the same general product adaptability according to the method by Fletcher et al. (2009). However, since the three color-toner cartridges in the HP LaserJet Pro printer can be changed separately, while the three color-toner cartridges in the Samsung Xpress printer are grouped as a module, the HP LaserJet Pro printer should have better general product adaptability. In this work, design nodes can be grouped into modules for modelling the product design.



Dell Latitude laptop with adaptable components

MacBook Pro laptop without adaptable components

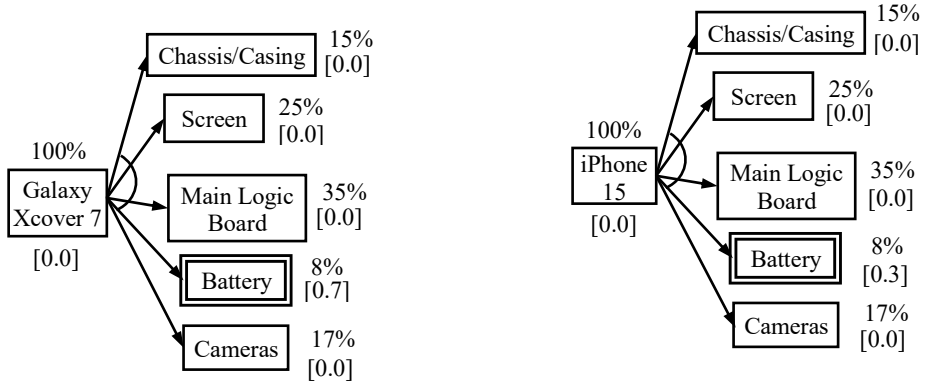
(a). Adaptable nodes and unadaptable nodes



HP LaserJet Pro printer with 3 color-toner cartridges

Samsung Xpress printer with 1 three-color toner cartridge module

(b). Nodes in modules



Galaxy Xcover 7 with battery changeable by user

iPhone 15 with battery changeable by service person

(c). Probabilities of adaptable nodes

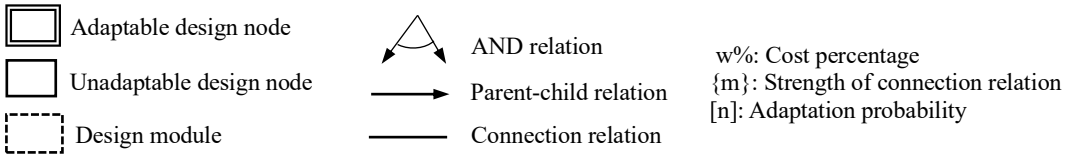


Figure 5.2. Comparison of designs considering three factors that influence the general product adaptability

(3) The influence of the probabilities of components/sub-assemblies changes

In the method by Fletcher et al. (2009), the probabilities of design node changes were not considered. In the real world, different components may have different chances to be changed due to different conditions in requirements, design, manufacturing, and operation. For example, the two products shown in Figure 5.2(c) are considered with the same general product adaptability according to the method by Fletcher et al. (2009). However, since the battery of the Galaxy Xcover 7 can be replaced by the user, while the battery of the iPhone 15 must be changed by an Apple professional technician, the Galaxy Xcover 7 has better general product adaptability. In this work, design nodes are associated with probabilities, representing the chances of their changes for product adaptation.

5.3. Evaluation of General Product Adaptability Considering the Three Influencing Factors

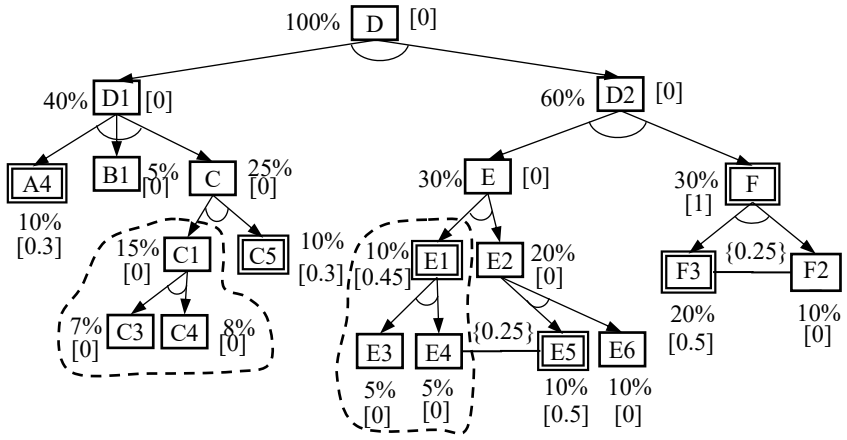
In this research, the general product adaptability introduced by Fletcher et al. (2009) has been improved by considering the three influencing factors: (1) adaptable nodes and unadaptable nodes, (2) nodes in modules, and (3) probabilities of node adaptations.

5.3.1. Modelling of a design solution with the actual product architecture

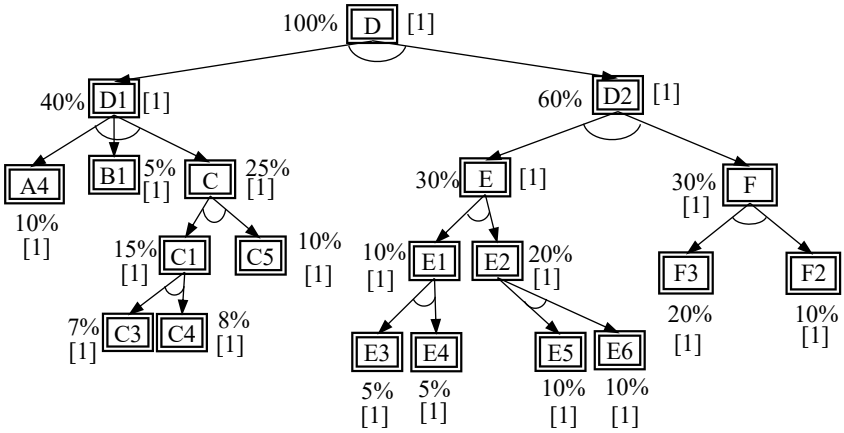
The actual product architecture of a design solution is modelled primarily by a tree with AND relations, as shown in Figure 5.3(a).

A design node in the tree represents a partial design solution, such as a component (e.g., a gear) or a sub-assembly (e.g., a gear-pair mechanism with two gears). A super-node is composed of sub-nodes with an AND relation. A node is associated with its cost percentage, representing its importance in the whole product. The relations between two nodes are classified into two categories:

- *P-relation:* the parent-child relation between a super-node and its sub-node
- *C-relation*: the connection relation considering functions, shapes, etc.



(a). An actual product architecture



(b). An ideal segregated product architecture

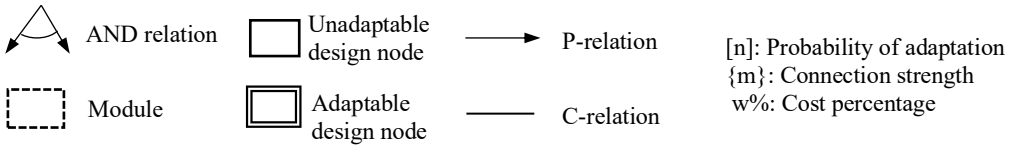


Figure 5.3. Actual and ideal segregated product architectures for modelling a product design solution

The strength of a connection relation is defined by a value between 0 and 1, where 0 represents no relation and 1 represents an extremely strong relation. The strength of a parent-child relation between a super-node and its sub-node is 1. When C-relations are considered, the actual product architecture is defined by a graph.

- *Adaptable nodes and unadaptable nodes*

  Design nodes are classified into two categories: adaptable nodes and unadaptable nodes. An adaptable node (e.g., A4 in Figure 5.3(a)) can be removed, added, or replaced by another one usually with different shape and/or function for product adaptation. An unadaptable node (e.g., B1 in Figure 5.3(a)) cannot be changed for product adaptation.

- *Nodes in modules*

  Design nodes can be grouped into modules (e.g., C1, C3, and C4 in Figure 5.3(a)). For product adaptation, all the design nodes in a module should be changed together.

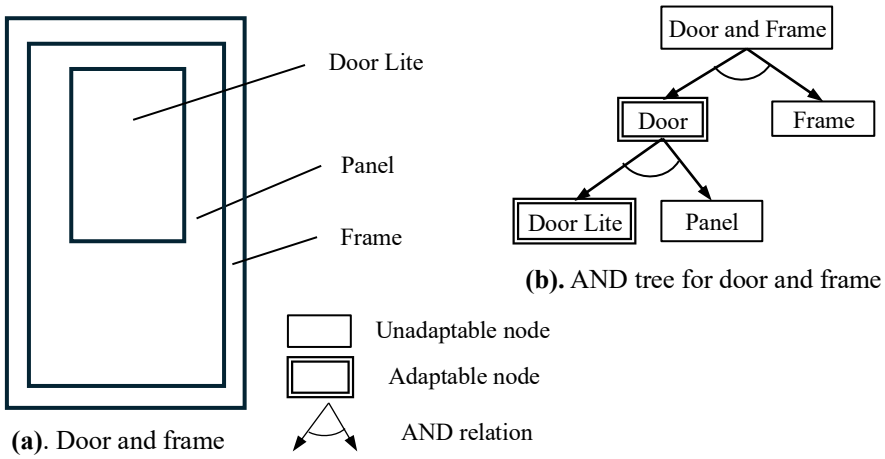
- *Probabilities of node changes*

  Chances of node changes for product adaptation are defined by probabilities (e.g., 0.3 for A4 in Figure 5.3(a)). The probability of change for an unadaptable node is 0.

The following rules should be satisfied for modelling the relation between a super-node and its sub-nodes with an AND relation using adaptable nodes and unadaptable nodes.

- An unadaptable super-node can be supported by adaptable sub-nodes and unadaptable sub-nodes with an AND relation (e.g., unadaptable super-node D1 is supported by 1 adaptable sub-node A4 and 2 unadaptable sub-nodes B1 and C in Figure 5.3(a)). An adaptable sub-node can be changed for product adaptation without changing the whole super-node.
- An adaptable super-node can be supported by adaptable sub-nodes and unadaptable sub-nodes with an AND relation (e.g., adaptable super-node F is supported by 1 adaptable sub-node F3 and 1 unadaptable sub-node F2 in Figure 5.3(a)). An adaptable sub-node can be changed for product adaptation without changing the whole super-node. When the super-node is changed, its sub-nodes should also be changed.
- When a super-node and its sub-nodes with an AND relation are grouped into a module, since each of these sub-nodes cannot be changed independently, all the sub-nodes are unadaptable nodes. The super-node can be an adaptable node (e.g., E1 in Figure 5.3(a)) or unadaptable node (e.g., C1 in Figure 5.3(a)).

Figure 5.4 shows an example with a door and its frame modelled by an AND tree using adaptable nodes and unadaptable nodes. The door lite can be changed independently (e.g., a transparent glass door lite can be replaced by a frosted glass one to improve the privacy). When the door is changed (e.g., from a wooden door to a metallic one to enhance security and durability), both the door lite and the panel should be replaced.



(a). Door and frame

(b). AND tree for door and frame

Figure 5.4. Unadaptable and adaptable nodes for modelling a door and its frame

Parameters in the actual product architecture are determined based on the following guidelines.

- *Adaptation probability*

  The adaptation probability of a node in the operation stage is defined by a value between 0 and 1. Various factors, such as the technology evolution rate, the level of customer excitement for new functions, the scalability of the component to accommodate functional change, and the compliance of the component with upcoming standards, are considered to estimate the probabilities of adaptable nodes.

- *Strength of connection relation*

  The strength of the connection relation between two nodes is defined by a value between 0 and 1. When the change of a node does not affect the other node, the strength of this connection relation is defined as 0. When the change of a node leads to a complete change of the other node, the strength of this connection relation is defined as 1. Various factors, such as interface standardization, interactions or flows of materials, information and energy, functional

dependency, and geometric shape, are considered to estimate the strengths of connection relations.

- *Cost percentage*

  Cost percentages of nodes are calculated from the costs of the bottom nodes in the product AND tree. The costs of bottom nodes are estimated considering various factors such as materials, manufacturing processes, production volumes, and suppliers and logistics. When a super-node is composed of sub-nodes with an AND relation, the cost of the super-node is the sum of the costs of its sub-nodes. The cost of the root node of the AND tree is used as the total cost of the product. The cost percentage of a node is calculated by dividing the cost of this node by the total cost of the product.

5.3.2. Modelling of the ideal segregated product architecture for a design solution

From the actual product architecture, an ideal segregated product architecture, representing an ideal adaptable product, can be created, as shown in Figure 5.3(b). In this architecture, since the modification of any node does not influence other nodes, the product is ideal for product adaptation. It should be noted that the ideal segregated product architecture is usually not achievable. However, this architecture can be used as a baseline to determine the relative general adaptability of the actual product.

The following rules are used to generate the ideal segregated product architecture from the actual product architecture:

- All unadaptable design nodes are converted into adaptable design nodes.
- Adaptation probabilities of all design nodes are assigned as 1s.
- Design modules are deleted.
- Connection relations are deleted.

5.3.3. Evaluation of general product adaptability

The general product adaptability $A^{(G)}$ is defined by:

$$A^{(G)} = \frac{\sum_{\text{Actual}} R^{(P)}}{\sum_{\text{Ideal}} R^{(P)} + \sum_{\text{Actual}} R^{(C)}} = \frac{\sum_{\text{Actual}} R_{i,j}^{(P)}}{\sum_{\text{Ideal}} R_{i,j}^{(P)} + \sum_{\text{Actual}} R_{i,j}^{(C)}} \tag{5.4}$$

where $\sum_{\text{Actual}} R^{(P)}$ represents the influence of parent-child relations (i.e., P-relations) by the actual product architecture, $\sum_{\text{Ideal}} R^{(P)}$ represents the influence of the parent-child relations (i.e., P-relations) by the ideal segregated product architecture, and $\sum_{\text{Actual}} R^{(C)}$ represents the influence of connection relations (i.e., C-relations) by the actual product architecture.

- $R_{i,j}^{(P)}$ *in the actual product architecture:*

A P-relation between the *i-th* super-node and the *j-th* sub-node in the actual product architecture is calculated by the relation strength between the two nodes $r_{ij}^{(P)}$, the importance of the *j-th* sub-node w_j, and the adaptation probability of the *j-th* sub-node p_j using:

$$R_{i,j}^{(P)} = r_{ij}^{(P)}(p_j w_j) = p_j w_j \tag{5.5}$$

where the strength of the relation between the two nodes $r_{ij}^{(P)}$ is defined as 1. When both the *i-th* node and the *j-th* node are within the same module, the relation is then not considered, since this P-relation doesn't influence the adaptation of the product.

- $R_{i,j}^{(P)}$ *in the ideal segregated product architecture:*

A P-relation between the *i-th* super-node and the *j-th* sub-node in the ideal segregated product architecture is calculated by the relation strength between the two nodes $r_{ij}^{(P)}$, the importance of the *j-th* sub-node w_j, and the adaptation probability of the *j-th* sub-node p_j using:

$$R_{i,j}^{(P)} = r_{ij}^{(P)}(p_j w_j) = w_j \tag{5.6}$$

where the strength of the relation between the two nodes $r_{ij}^{(P)}$ is defined as 1, and the adaptation probability of the *j-th* sub-node p_j is also defined as 1.

- $R_{i,j}^{(C)}$ *in the actual product architecture:*

A C-relation between the *i-th* node and the *j-th* node in the actual product architecture is calculated by the strength of the relation between the two nodes $r_{ij}^{(C)}$, the importance of the two nodes w_i and w_j, and the adaptation probabilities of the two nodes p_i and p_j using:

$$R_{i,j}^{(C)} = r_{ij}^{(C)}\left(p_i w_i + p_j w_j\right) \tag{5.7}$$

When both the *i-th* node and the *j-th* node are within the same module, the relation is then not considered, since this C-relation doesn't influence the adaptation of the product. When the *i-th* node or the *j-th* node is from a module, the cost percentage and adaptation probability of the root node for that module are used as importance and probability of the *i-th* node or the *j-th* node.

The relations for the actual product architecture given in Figure 5.3(a) and the ideal segregated product architecture given in Figure 5.3(b) are provided in Table 5.1 and Table 5.2, respectively. The general product adaptability is obtained using Equation (5.4).

Table 5.1. Relations in the actual product architecture

i-j Nodes	Relation	p_i	p_j	w_i	w_j	r_{ij}	$R_{i,j}^{(P)}$	$R_{i,j}^{(C)}$
D-D1	P-relation	0	0	1	0.4	1	0	-
D1-A4	P-relation	0	0.3	0.4	0.1	1	0.03	-
D1-B1	P-relation	0	0	0.4	0.05	1	0	-
D1-C	P-relation	0	0	0.4	0.25	1	0	-
C-C1	P-relation	0	0	0.25	0.15	1	0	-
C-C5	P-relation	0	0.3	0.25	0.1	1	0.03	-
D-D2	P-relation	0	0	1	0.6	1	0	-
D2-E	P-relation	0	0	0.6	0.3	1	0	-
D2-F	P-relation	0	1	0.6	0.3	1	0.3	-
E-E1	P-relation	0	0.45	0.3	0.1	1	0.045	-
E-E2	P-relation	0	0	0.3	0.2	1	0	-
E2-E5	P-relation	0	0.5	0.2	0.1	1	0.05	-
E2-E6	P-relation	0	0	0.2	0.1	1	0	-
F-F3	P-relation	1	0.5	0.3	0.2	1	0.1	-
F-F2	P-relation	1	0	0.3	0.1	1	0	-
E4-E5	C-relation	0.45	0.5	0.1	0.1	0.25	-	0.0237
F3-F2	C-relation	0.5	0	0.2	0.1	0.25	-	0.0250
Sum							**0.555**	**0.0487**

Table 5.2. Relations in the ideal segregated product architecture

i-j Nodes	Relation	p_i	p_j	w_i	w_j	r_{ij}	$R_{i,j}^{(P)}$	$R_{i,j}^{(C)}$
D-D1	P-relation	1	1	1	0.4	1	0.4	-
D1-A4	P-relation	1	1	0.4	0.1	1	0.1	-
D1-B1	P-relation	1	1	0.4	0.05	1	0.05	-
D1-C	P-relation	1	1	0.4	0.25	1	0.25	-
C-C1	P-relation	1	1	0.25	0.15	1	0.15	-
C-C5	P-relation	1	1	0.25	0.1	1	0.1	-
C1-C3	P-relation	1	1	0.15	0.07	1	0.07	-
C1-C4	P-relation	1	1	0.15	0.08	1	0.08	-
D-D2	P-relation	1	1	1	0.6	1	0.6	-
D2-E	P-relation	1	1	0.6	0.3	1	0.3	-
D2-F	P-relation	1	1	0.6	0.3	1	0.3	-
E-E1	P-relation	1	1	0.3	0.1	1	0.1	-
E-E2	P-relation	1	1	0.3	0.2	1	0.2	-
E1-E3	P-relation	1	1	0.1	0.05	1	0.05	-
E1-E4	P-relation	1	1	0.1	0.05	1	0.05	-
E2-E5	P-relation	1	1	0.2	0.1	1	0.1	-
E2-E6	P-relation	1	1	0.2	0.1	1	0.1	-
F-F3	P-relation	1	1	0.3	0.2	1	0.2	-
F-F2	P-relation	1	1	0.3	0.1	1	0.1	-
Sum							**3.30**	**-**

$$A^{(G)} = \frac{0.555}{3.30 + 0.0487} = 0.165$$

The value of general product adaptability is between 0 and 1, where 0 indicates no adaptability and 1 indicates the maximum adaptability (i.e., the product with the ideal segregated product architecture).

5.3.4 Comparative studies

Our newly introduced general product adaptability measure has been compared with the general product adaptability measure developed by Fletcher et al. (2009) using the three examples shown in Figure 5.2. Table 5.3 shows the comparison results.

To obtain the general product adaptability measures using the method by Fletcher et al. (2009), the following rules were used first to convert the 6 graphs shown in Figure 5.2.

- All unadaptable design nodes were converted into adaptable design nodes.
- Design modules for grouping design nodes were deleted.
- Adaptation probabilities of all design nodes were assigned as 1s.

Table 5.3. Results from the comparative studies

(a). Dell Latitude laptop vs. MacBook Pro laptop

Method	**Method by Fletcher et al. (2009)**		**Our New Method**	
Product	**Dell**	**MacBook**	**Dell**	**MacBook**
$\sum_{\text{Actual}} R_{i,j}^{(P)}$	1	1	0.15	0
$\sum_{\text{Ideal}} R_{i,j}^{(P)}$	1	1	1	1
$\sum_{\text{Actual}} R_{i,j}^{(\text{C})}$	0.11	0.11	0.01	0
$A^{(G)}$	0.90	0.90	0.148	0

(b). HP LaserJet Pro printer vs. Samsung Xpress printer

Method	**Method by Fletcher et al. (2009)**		**Our New Method**	
Product	**HP**	**Samsung**	**HP**	**Samsung**
$\sum_{\text{Actual}} R_{i,j}^{(P)}$	2.05	2.05	1.79	1.34
$\sum_{\text{Ideal}} R_{i,j}^{(P)}$	2.05	2.05	2.05	2.05
$\sum_{\text{Actual}} R_{i,j}^{(\text{C})}$	0.074	0.074	0.074	0.074
$A^{(G)}$	0.97	0.97	0.84	0.63

(c). Galaxy Xcover 7 vs. iPhone 15

Method	**Method by Fletcher et al. (2009)**		**Our New Method**	
Product	**Galaxy**	**iPhone**	**Galaxy**	**iPhone**
$\sum_{\text{Actual}} R_{i,j}^{(P)}$	1	1	0.056	0.024
$\sum_{\text{Ideal}} R_{i,j}^{(P)}$	1	1	1	1
$\sum_{\text{Actual}} R_{i,j}^{(\text{C})}$	0	0	0	0
$A^{(G)}$	1	1	0.056	0.024

Using the method by Fletcher et al. (2009), the two products in each of the three comparison cases were found to have the same general product adaptability values. Using our newly developed method, we can reach the following conclusions.

- Case (a):

  The Dell Latitude laptop has better general product adaptability, since the RAM and battery in the Dell Latitude laptop can be upgraded or replaced, while the RAM and battery in the MacBook Pro laptop are integrated into the motherboard and cannot be changed.

- Case (b):

  The HP LaserJet Pro printer has better general product adaptability, since the three color-toner cartridges in the HP LaserJet Pro printer can be changed separately, while the three color-toner cartridges in the Samsung Xpress printer are grouped as a module.

- Case (c):

  The Galaxy Xcover 7 has better general product adaptability, since the battery of the Galaxy Xcover 7 can be replaced by the user, while the battery of the iPhone 15 must be changed by an Apple professional technician.

5.4. Process of Adaptable Product Design Considering the General Product Adaptability

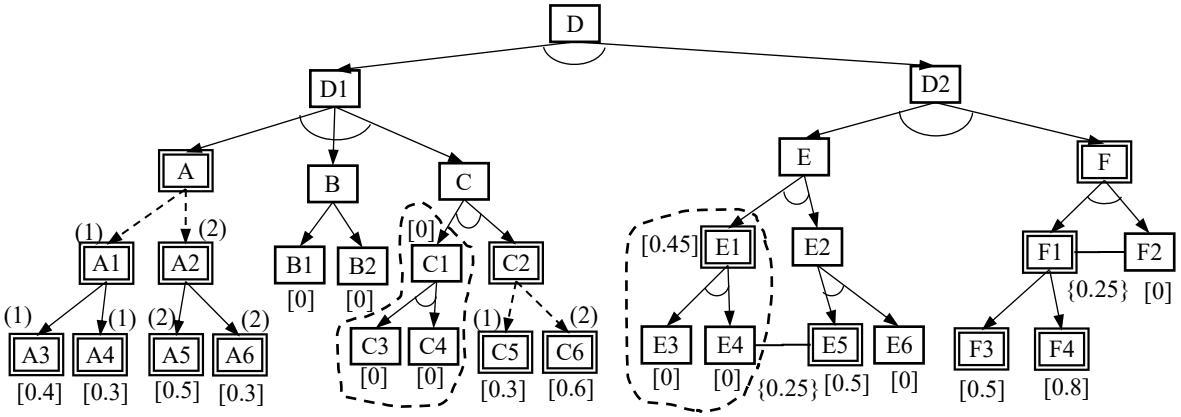
The adaptable product design approach developed previously in Chapter 4 has also been improved in this research, considering the three factors in product modelling: (1) adaptable nodes and unadaptable nodes, (2) nodes in modules, and (3) probabilities of node adaptations. This new general product adaptability evaluation method has been used to evaluate adaptable product design candidates.

5.4.1. Modelling for adaptable product design

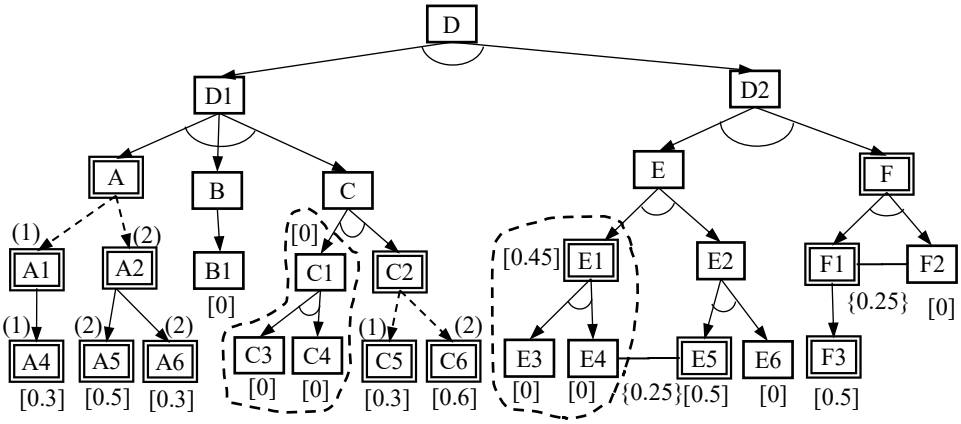
Changes of models for the design of an adaptable product are shown in Figure 5.5.

(a) Modelling of the generic product design

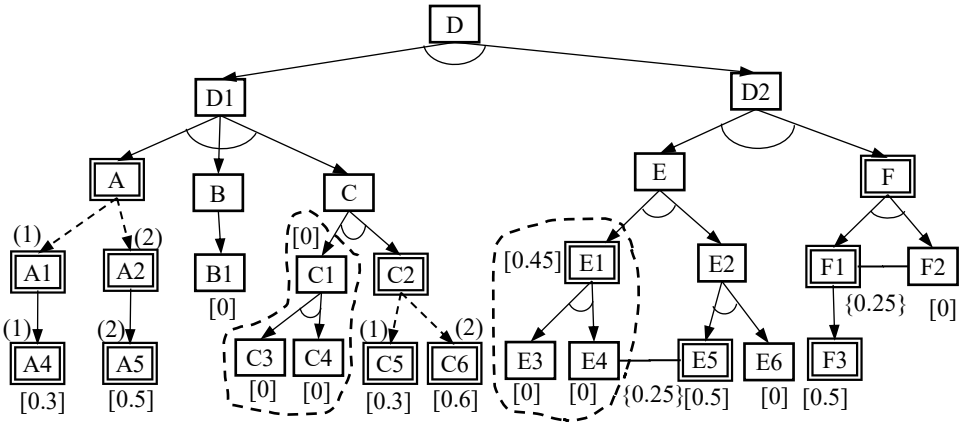
The generic product, considering all possible original design configurations and adapted design configurations, is modelled by an AND-OR tree with connection relations, as shown in Figure 5.5(a). Nodes of the tree are used to define components and sub-assemblies. Design nodes are classified into adaptable nodes and unadaptable nodes. The adaptable nodes are associated with adaptation probabilities. Design nodes can be grouped into modules. A super-node and its sub-node are linked by a parent-child relation (i.e., P-relation).



(a). An AND-OR tree with connection relations considering alternative solutions of original design configurations and adapted design configurations



(b). A specific original design configuration with alternative solutions of adapted design configurations



(c). A final solution with a specific original design configuration and a specific adapted design configuration

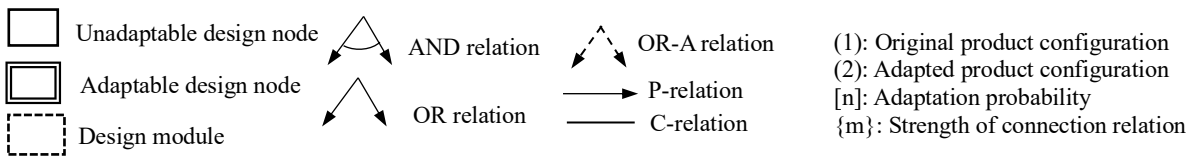


Figure 5.5. Changes of models for design of an adaptable product

The relations among sub-nodes of a super-node are classified into three categories:

- *AND relation*: when all the sub-nodes are required to support the super-node,
- *OR relation*: when only one sub-node is required to support the super-node, and
- *OR-A (i.e., OR for adaptation) relation*: when different sub-nodes are used for different configurations of the product, considering product adaptation.

Two nodes can also be linked with a connection relation (i.e., C-relation).

Cases of product adaptation from the original design configurations to the adapted design configurations modelled using the OR-A relations are shown in Figure 5.6.

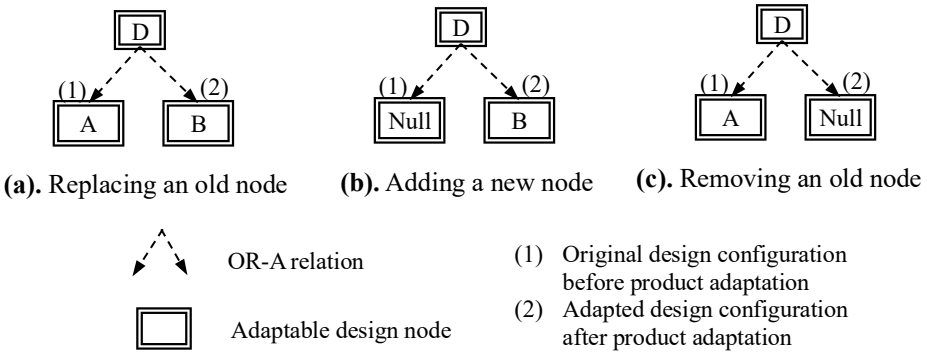


Figure 5.6. Three cases for product adaptation modelled by OR-A relations

The generic product AND-OR tree, as shown in Figure 5.5(a), should satisfy the following rules:

- For a super-node, when its sub-nodes are associated with an AND relation (e.g., Node F), a sub-node can be either adaptable or unadaptable.
- For a super-node, when its sub-nodes are associated with an OR relation, if the super-node is adaptable (e.g., Node F1), all the sub-nodes are adaptable. If the super-node is unadaptable (e.g., Node B), all the sub-nodes are unadaptable.
- For an adaptable super-node, when its sub-nodes are associated with an OR-A relation (e.g., Node A), all the sub-nodes should be adaptable for different product configurations, considering product adaptation. An unadaptable super-node cannot have sub-nodes associated with an OR-A relation.

- For nodes in a module, the super-node can be either adaptable (e.g., Node E1) or unadaptable (e.g., Node C1), while the sub-nodes are always unadaptable. Only AND relations are used to associate sub-nodes in a module.
- Adaptable leaf nodes (e.g., Nodes F3 and E5) are assigned adaptation probabilities between 0 and 1, representing the chances that the nodes can be changed for product adaptation. Unadaptable nodes (e.g., Node B1) are assigned adaptation probabilities of 0s.
- If a super-node and its sub-nodes form a module (e.g., Nodes E1, E3, and E4), the adaptation probability of the super-node is selected as the adaptation probability of the whole module.

(b) Creation of a specific original design configuration with alternative solutions of the adapted design configurations

Tree-based search is used to create specific original design configuration candidates from the generic product design AND-OR tree. Figure 5.5(b) shows a specific original design configuration created from the AND-OR tree given in Figure 5.5(a). The following rules are used to generate a specific original design configuration with alternative solutions of the adapted design configuration:

- The root node should be selected first (e.g., Node D).
- If the selected node has sub-nodes associated with an AND relation (e.g., Node D1), all these sub-nodes should be selected.
- If the selected node has sub-nodes associated with an OR relation (e.g., Node B) and the selected node is not only in the original design configuration or the adapted design configuration, only one sub-node should be selected.
- If the selected node is an adaptable design node and its sub-nodes are associated with an OR-A relation (e.g., Nodes A and C2), all the sub-nodes should be selected.
- If the selected node is an adaptable design node for the original design configuration and its sub-nodes are associated with an OR relation (e.g., Node A1), only one sub-node should be selected.

- If the selected node is an adaptable design node for the adapted design configuration and its sub-nodes are associated with an OR relation (e.g., Node A2), all the sub-nodes should be selected.

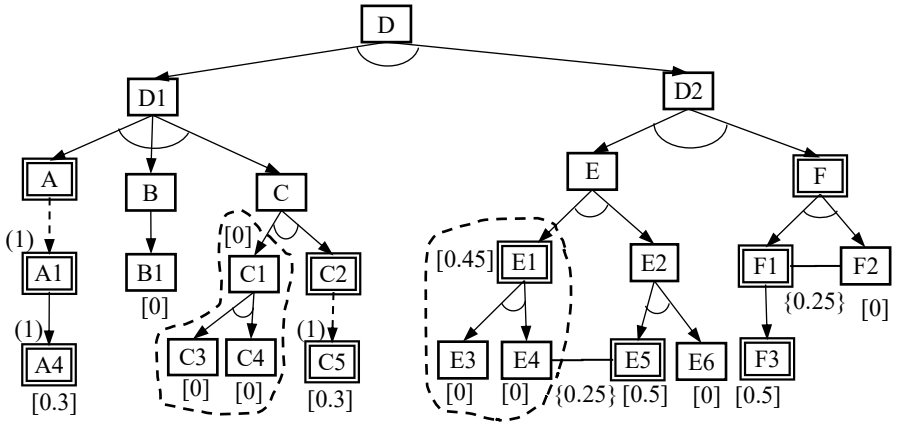
(c) Creation of the final solution with a specific original design configuration and a specific adapted design configuration

Tree-based search is used further to create the final solution candidates. Figure 5.5(c) shows a final solution created from the AND-OR tree given in Figure 5.5(b). The following rules are used to generate a final solution with a specific original design configuration and a specific adapted design configuration:

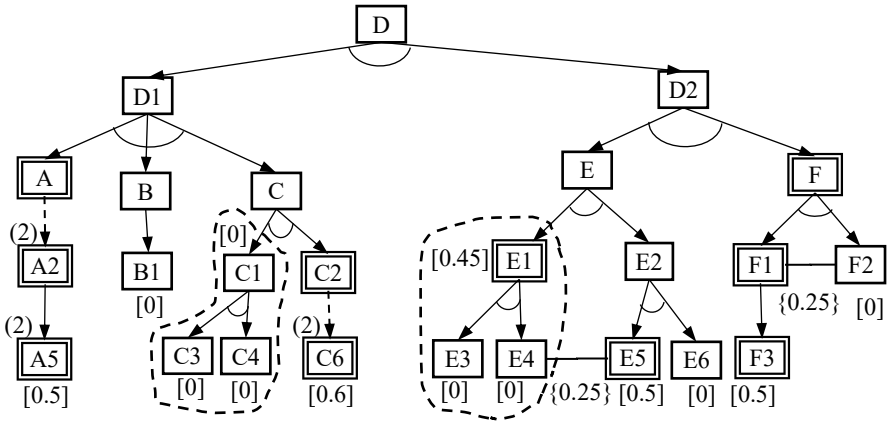
- The root node should be selected first (e.g., Node D).
- If the selected node has sub-nodes associated with an AND relation (e.g., Node D1), all these sub-nodes should be selected.
- If the selected node is an adaptable design node and its sub-nodes are associated with an OR-A relation (e.g., Nodes A and C2), all the sub-nodes should be selected.
- If the selected node is an adaptable design node for the adapted design configuration and its sub-nodes are associated with an OR relation (e.g., Node A2), only one sub-node should be selected.

From the final solution, the original design configuration before product adaptation and the adapted product configuration after product adaptation are created. Figure 5.7 shows the original design configuration and the adapted design configuration created from the AND-OR tree given in Figure 5.5(c). The original design configuration and the adapted design configuration are created based on the following rules.

- The root node should be selected first (e.g., Node D).
- If the selected node has sub-nodes associated with an AND relation (e.g., Node D1), all these sub-nodes should be selected.
- If the selected node is an adaptable design node and its sub-nodes are associated with an OR-A relation (e.g., Node A), only one sub-node for the original design configuration or the adapted design configuration should be selected.



(a). The original design configuration



(b). The adapted design configuration

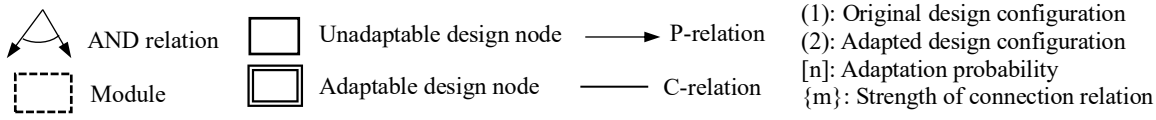


Figure 5.7. The original design configuration and the adapted design configuration

5.4.2. Evaluation for adaptable product design

The different design solution candidates are evaluated such that the optimal design solution can be identified to manufacture the physical product. In addition to the traditional evaluation measures such as performance and cost, the general product adaptability is also used to evaluate design candidates.

5.4.2.1. Evaluation of the general product adaptability

In this work, the following two types of adaptable product designs are considered.

- *Design of an adaptable product without specific adaptation requirements*

  For this type of design, evaluation of the general product adaptability is conducted, such that the product can be easily changed in the operation stage to satisfy the new requirements, which are unknown at the design stage.

- *Design of an adaptable product with specific adaptation requirements*

  For this type of design, both the specific product adaptability and the general product adaptability are considered. The specific product adaptability is considered to achieve the design of the adaptable product that can be changed to satisfy the specific requirements with the lowest effort. The general product adaptability is considered to achieve the design of the adaptable product that can be changed to satisfy other new requirements that are unknown at the design stage.

Based on the above discussions, the general product adaptability is used to evaluate the original product design configuration before the product adaptation, such that the product can be adapted easily to satisfy the new requirements, which are unknown at the design stage. Since the original product design configuration, as shown in Figure 5.7(a), is created from the generic AND-OR tree, OR and OR-A relations may also be used for modelling this design configuration. Since the general product adaptability is used to evaluate a design that is modelled only by a tree with AND relations and connection relations, the original product design configuration created from the AND-OR tree needs to be converted into a tree with only AND relations and connection relations. The following rules are used for this conversion process, as shown in Figure 5.8.

- The root node should be selected first (e.g., Node D).
- If the selected super-node has sub-nodes associated with an AND relation (e.g., Node D1), all these sub-nodes should be selected.
- For a super-node with only one sub-node (e.g., Nodes A, B, and F1), the super-node and the P-relation below the node should be deleted. If this super-node has a connection relation with

another node (e.g., Node F1), the connection relation should be transferred from the super-node to the sub-node.

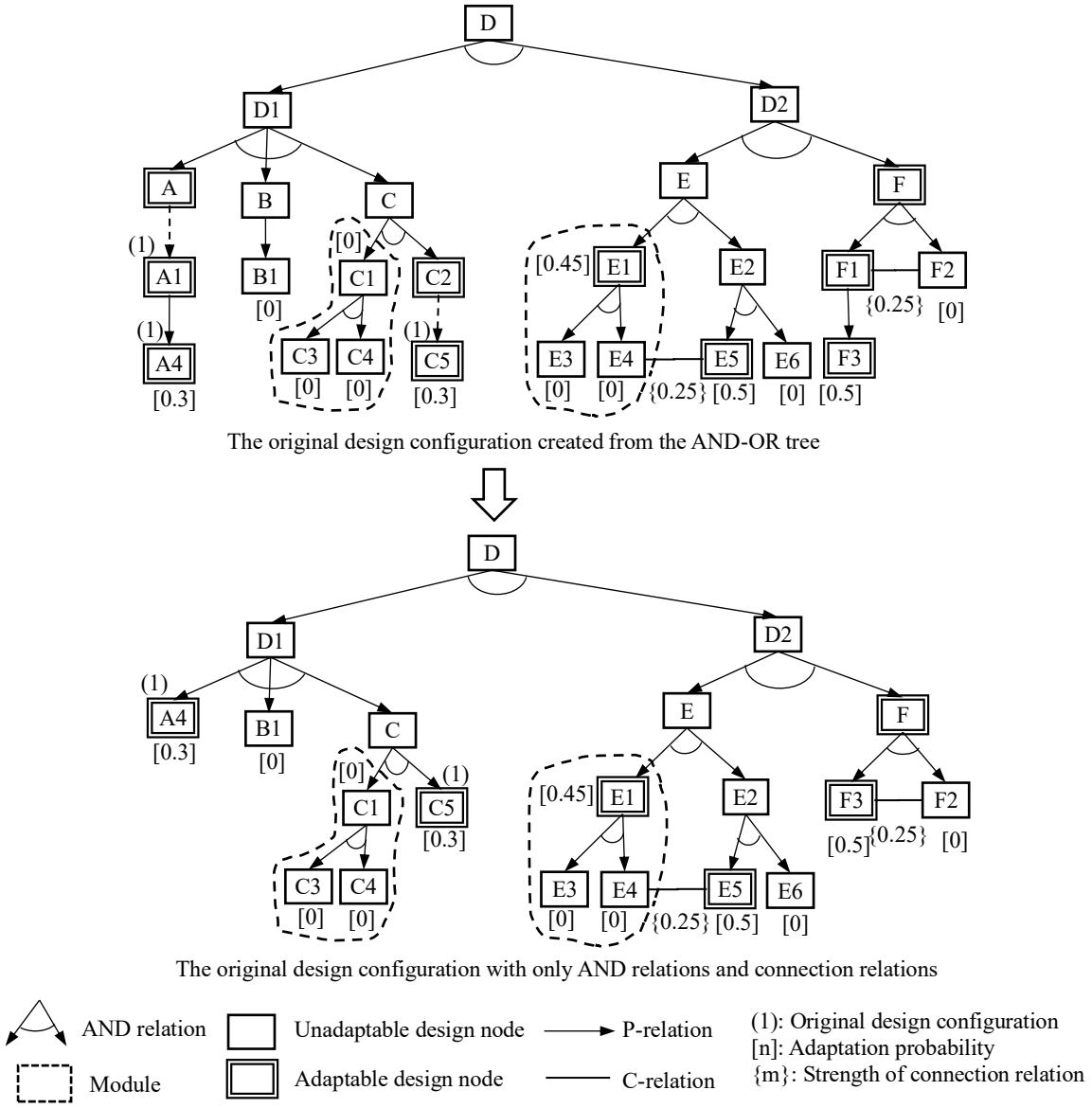


Figure 5.8. Creation of the original product design configuration AND tree

For the original design configuration modelled by the AND tree as shown in Figure 5.8, it is further changed to the actual product architecture as shown in Figure 5.3(a) by adding the following descriptions.

- For an adaptable node without adaptation probability (e.g., Node F), its adaptation probability is assigned 1.

- For an unadaptable node (e.g., Node C), its adaptation probability is assigned 0.
- For each design node, its cost percentage in the whole product is calculated and used as the importance of this design node.

5.4.2.2. The overall evaluation index

In addition to the general product adaptability, other evaluation measures such as performance and cost are also used to evaluate the design solution candidate. Since each design node is associated with design parameters, a design solution $S_i\ (i = 1, 2, \dots, p)$ can be defined by the parameters of all design nodes $\boldsymbol{X_i}$.

A feasible solution with its parameters is evaluated by m evaluation measures.

$$F_j = f_j(S_i) = f_j(\boldsymbol{X_i}),\ i = 1, 2, \dots, p;\ j = 1, 2, \dots, m \tag{5.8}$$

where F_j represents an evaluation measure such as performance or cost, and $f_j()$ is the numerical function to obtain F_j.

Since different evaluation measures are usually defined by different units, these evaluation measures F_j are first converted into comparable evaluation indices I_j between 0 and 1, representing satisfaction levels in these evaluation aspects.

$$I_j = g_j(F_j) = g_j\big(f_j(\boldsymbol{X_i})\big),\ i = 1, 2, \dots, p;\ j = 1, 2, \dots, m \tag{5.9}$$

where $g_j()$ is the numerical function to obtain I_j.

Similar to Chapter 3 and Chapter 4, the method developed by Yang et al. (2006) is also used to convert evaluation measures into evaluation indices in this research. First, data points considering evaluation measures and their corresponding evaluation indices are obtained from customers and/or engineers. A linear or a non-linear relationship between the evaluation measure and the evaluation index is then defined by a polynomial function. The least-squares curve-fitting method is subsequently used to obtain the coefficients of the polynomial function.

Then, all these evaluation indices are integrated for the evaluation of a design solution. The overall evaluation index, $I(\boldsymbol{X_i})$, is defined by:

$$I(\boldsymbol{X_i}) = \frac{W_{(G)}A^{(G)}+\sum_{j=1}^{m}(W_j I_j)}{W_{(G)}+\sum_{j=1}^{m} W_j} = \frac{W_{(G)}A^{(G)}+\sum_{j=1}^{m}\left(W_j g_j(f_j(\boldsymbol{X_i}))\right)}{W_{(G)}+\sum_{j=1}^{m} W_j} \quad (5.10)$$

where $W_{(G)}$ represents the weighting factor of the general product adaptability, and W_j represents the weighting factor of the *j-th* evaluation index. When the overall evaluation index is used as the objective function in optimization, the optimal adaptable product design process is then formulated as a multi-objective optimization problem considering the trade-offs among different evaluation measures, such as general product adaptability, performance, and cost.

5.4.3. Optimization for adaptable product design

The optimal solution is obtained through the multi-level optimization method (Xue 1997).

- *Parameter optimization:*

  For a solution S_i $(i = 1, 2, \dots, p)$ with the original design configuration and the adapted design configuration, parameter optimization is conducted to obtain the optimal values of these parameters and the optimal evaluation index corresponding to these optimal parameter values by:

$$\underset{w.r.t.\ \boldsymbol{X_i}}{max}\ I(\boldsymbol{X_i}) \quad (5.11)$$

  where $\boldsymbol{X_i}$ represents the vector of parameter variables, and $I(\boldsymbol{X_i})$ is the optimization objective function to be maximized.

- *Configuration optimization:*

  Each solution defined by its original design configuration and adapted design configuration is evaluated by its optimal evaluation index obtained through parameter optimization. Among all the solutions, the optimal one is achieved through configuration optimization by:

$$\underset{w.r.t.\ S_i}{max}\ I(\boldsymbol{X_i^*}) \quad (5.12)$$

where $I(\boldsymbol{X_i^*})$ is the optimal evaluation index corresponding to the optimal parameter values $\boldsymbol{X_i^*}$ for the *i-th* solution candidate S_i. When the number of solutions is not large, the exhaustive method is

used for configuration/parameter optimization. When the number is large, genetic programming (Rao 2009) is employed for configuration/parameter optimization.

5.5. Case Studies

The adaptable product design method introduced in this research was used to develop case studies to design an adaptable assistive device for individuals with disabilities. The general product adaptability was used to evaluate the design candidates. Effectiveness of our method was demonstrated by comparing the solutions achieved using the new method and the solutions obtained using the traditional design method.

5.5.1. Requirements

The initial requirement was to design a device for an individual with quadruple amputation to read an iPad independently with a stylus moving in X, Y, and Z directions through control using the arm stumps of the individual. A new requirement was considered later on to rotate the iPad about the X, Y, and Z axes in addition to the three translational motions of the stylus in the X, Y, and Z directions. Another new requirement was subsequently considered to further improve the assistive device to a robot with 6 axes to handle more tools to support various daily life activities, such as reading an iPad or eating a meal with a fork. The various requirements are summarized in Table 5.4.

Two case studies were implemented by using the different requirements for designing the adaptable device and testing the design solution, as shown in Table 5.4.

- *Case study 1: Design of an adaptable product without specific adaptation requirements*

  In this case study, only the original requirements O were used to design the original configuration of the adaptable device, considering the general product adaptability. The adaptation requirements A and B were used to modify the original configuration to the adapted configurations and to obtain the adaptation costs to test the new adaptable product design method.

- *Case study 2: Design of an adaptable product with specific adaptation requirements*

  In this case study, both the original requirements O and the adaptation requirements A were used to design the original configuration and the adapted configuration of the adaptable device, considering the general product adaptability. The adaptation requirements B were used to modify the product from its original configuration or adapted configuration to a new adapted configuration and to obtain the adaptation cost to test the new adaptable product design method.

Table 5.4. Requirements for the case studies

Requirement	Original Requirements: O	Adaptation Requirements: A	Adaptation Requirements: B
	• Read iPad • Translational motion of the stylus in X, Y, and Z directions • Control of the motion with arm stumps	• Read iPad • Translational motion of the stylus in X, Y, and Z directions • Rotational motion of the iPad about X, Y, and Z axes • Control of the motion with arm stumps	• Read iPad • Eat a meal with a fork • Translational motion of the tool in X, Y, and Z directions • Rotational motion of the tool about X, Y, and Z axes • Control of the motion with arm stumps
Case Study 1	• Used as known requirements in design	• Considered as unknown requirements and not used in design • Used to test the solution obtained by the design method	• Considered as unknown requirements and not used in design • Used to test the solution obtained by the design method
Case Study 2	• Used as known requirements in design	• Used as known requirements in design	• Considered as unknown requirements and not used in design • Used to test the solution obtained by the design method

5.5.2. Case study 1: Design of an adaptable product without specific adaptation requirements

5.5.2.1. Design of the adaptable product

The adaptable device was designed to satisfy the original requirements O given in Table 5.4. The device was composed of two sub-systems: the input sub-system to control the motion in X, Y, and Z directions with force sensors operated using the residual limbs of the user, and the output sub-system with beams to move the stylus in X, Y, and Z directions. The generic product design AND-OR tree considering various design solutions is shown in Figure 5.9. The geometric shapes

of the components, which are modelled by design nodes in the AND-OR tree, and explanations to the functions of these components are provided in Figure 5.10 and Table 5.5, respectively.

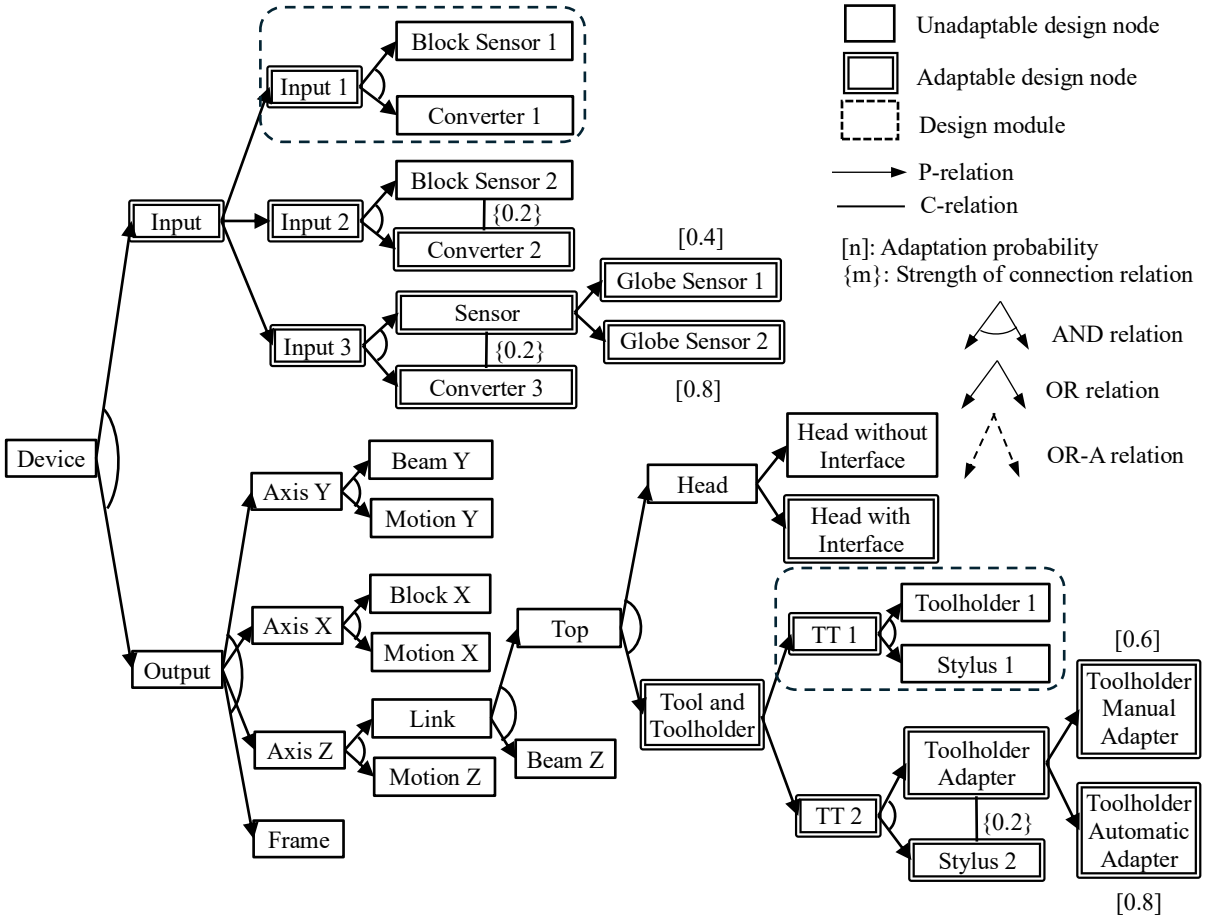
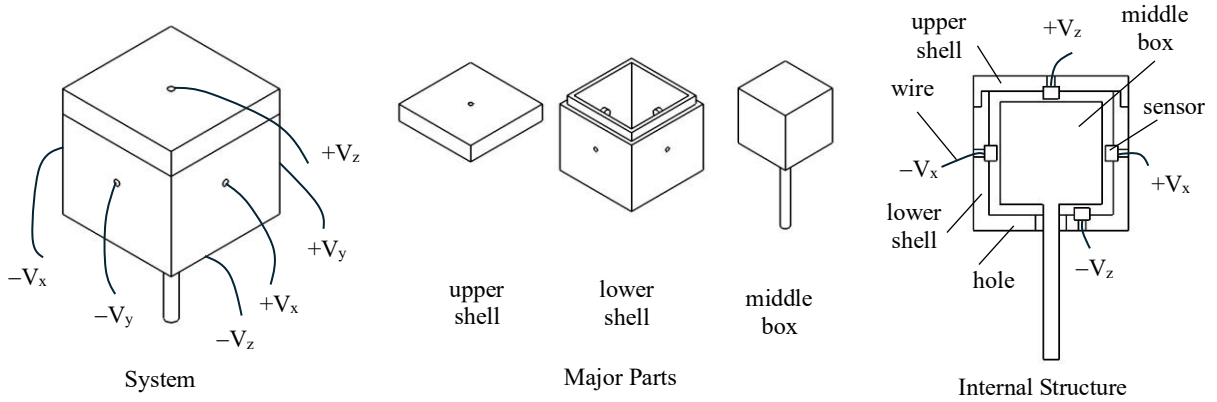
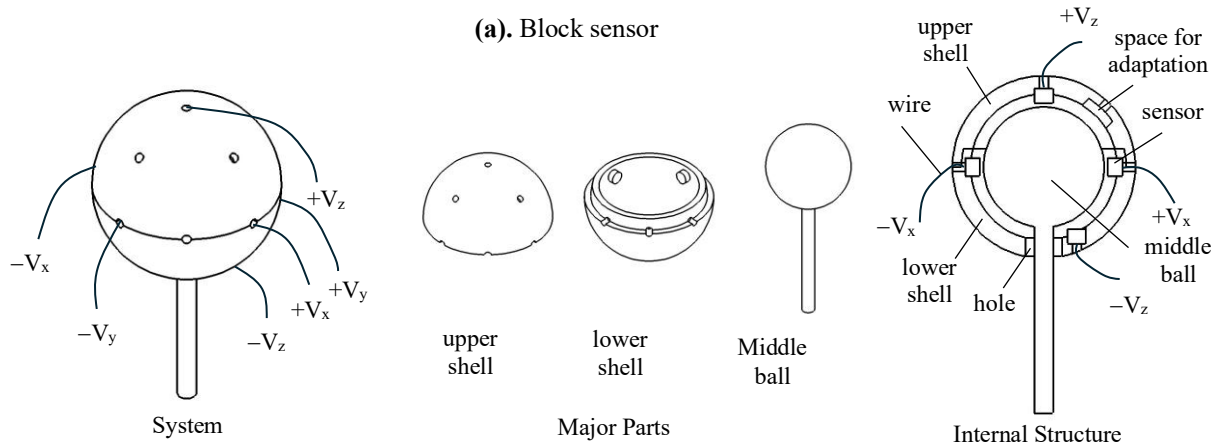


Figure 5.9. The generic product AND-OR tree for design of the adaptable device

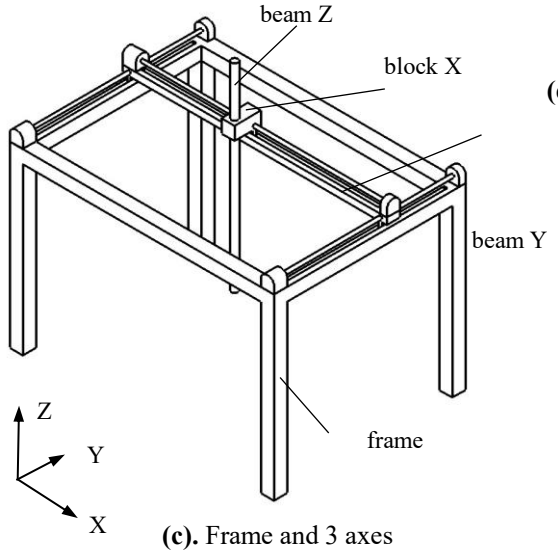
For the input sub-system, two types of sensors, the block sensors and the globe sensors, were considered. Both the block sensors and the globe sensors could be used to get forces in X, Y, and Z directions. The globe sensors could be adapted to obtain the rotational forces about X, Y, and Z axes. The output voltage signals from the sensors were transformed into control signals of translation motions in X, Y, and Z directions and rotational motions about X, Y, and Z axes (i.e., A, B, and C) through converters.



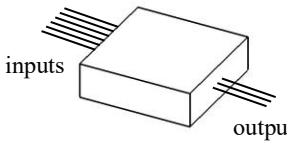
(a). Block sensor



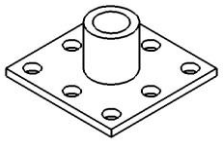
(b). Globe sensor (without space for adaptation; with space for adaptation)



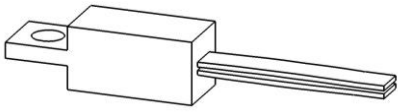
(c). Frame and 3 axes



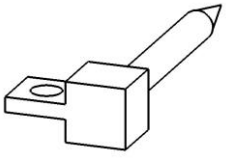
(d). Converter (hardwired; with interface)



(e). Head (without interface; with interface)



(f). Toolholder adapter (1: manual; 2: automatic)



(g). Toolholder and stylus module

(h). Stylus

Figure 5.10. Fundamental units for design of the adaptable device

Table 5.5. Components and their functions

Component	Function/Description
Block Sensor 1	• Capture forces in X, Y, and Z directions with output of 6 voltage signals • Connected with Converter 1 using hardwiring
Block Sensor 2	• Capture forces in X, Y, and Z directions with output of 6 voltage signals • Connected with Converter 2 using a standardized interface
Globe Sensor 1	• Capture forces in X, Y, and Z directions with output of 6 voltage signals • Can be adapted without the pre-manufactured spaces to also capture rotational forces about X, Y, and Z axes, with output of 12 voltage signals • Connected with Converter 3 using a standardized interface
Globe Sensor 2	• Capture forces in X, Y, and Z directions with output of 6 voltage signals • Can be adapted with the pre-manufactured spaces to also capture rotational forces about X, Y, and Z axes, with output of 12 voltage signals • Connected with Converter 3 using a standardized interface
Converter 1	• Convert input voltage signals into values of translational motions in X, Y, and Z directions • Connected with Block Sensor 1 using hardwiring
Converter 2	• Convert input voltage signals into values of translational motions in X, Y, and Z directions • Connected with Block Sensor 2 using a standardized interface
Converter 3	• Convert input voltage signals into values of up to 6 motions, including 3 translational motions in X, Y, and Z directions and 3 rotational motions about X, Y, and Z axes • Connected with either Globe Sensor 1 or Globe Sensor 2 using a standardized interface
Block X, Beam Y, Beam Z	• Major components with motions in X, Y, and Z directions
Frame	• Supporting structure for the motion mechanism
Motion X, Motion Y, Motion Z	• Power and mechanisms to control the motions in X, Y, and Z directions
Head without Interface	• Head at the end of Beam Z to connect the beam and the toolholder without digital communication between the beam and the toolholder
Head with Interface	• Head at the end of Beam Z to connect the beam and the toolholder with digital communication between the beam and the toolholder
Toolholder 1	• Toolholder to hold only Stylus 1
Stylus 1	• Specific stylus with shape to be held by Toolholder 1
Toolholder Manual Adapter	• Toolholder to hold various tools with different shapes • Manual changes of different tools by users
Toolholder Automatic Adapter	• Toolholder to hold various tools with different shapes • Automatic changes of different tools by users through digital communication with the Head
Stylus 2	• General stylus to be held by the toolholder adapter

For the output sub-system, motions in X, Y, and Z directions were obtained by Block X, Beam, Y and Beam Z with motors and motion control mechanisms. The bottom of Beam Z was connected to a head which was used to connect various toolholders and tools. Toolholders were used to hold tools such as stylus and fork.

From the generic product design AND-OR tree shown in Figure 5.9, a total of 24 solutions were created using the methods given in Section 5.4.1. By evaluating these solutions using the general product adaptability, the best one with the highest general product adaptability value was identified as shown in Figure 5.11. Geometric shapes of the components for this design are shown in Figure 5.12(a).

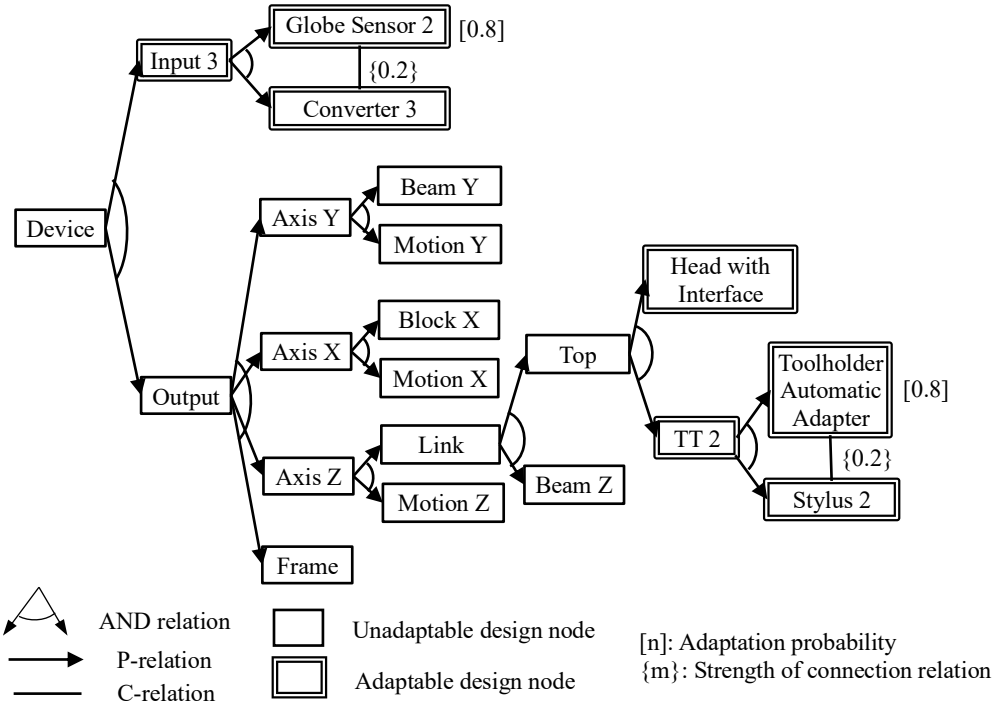


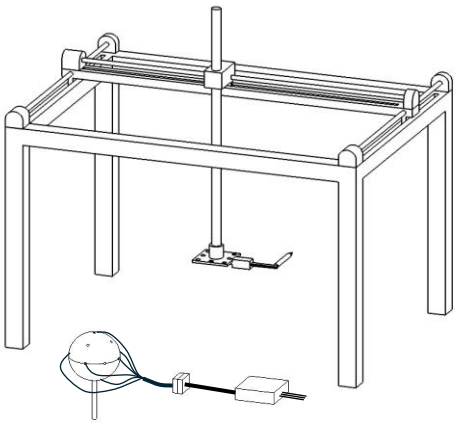
Figure 5.11. Adaptable design with the best general product adaptability

For this case study, since design parameter variables $\boldsymbol{X_i}$, evaluation measures F_j, and evaluation indices I_j were not considered, the optimization objective function defined by Equation (5.10) was changed as:

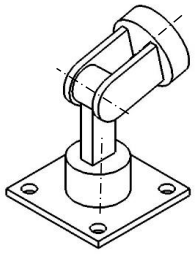
$$I = \frac{W_{(G)}A^{(G)} + \sum_{j=1}^{m}(W_j I_j)}{W_{(G)} + \sum_{j=1}^{m} W_j} = \frac{W_{(G)}A^{(G)}}{W_{(G)}} = A^{(G)} \tag{5.13}$$

The optimal adaptable product design solution considering the general product adaptability:

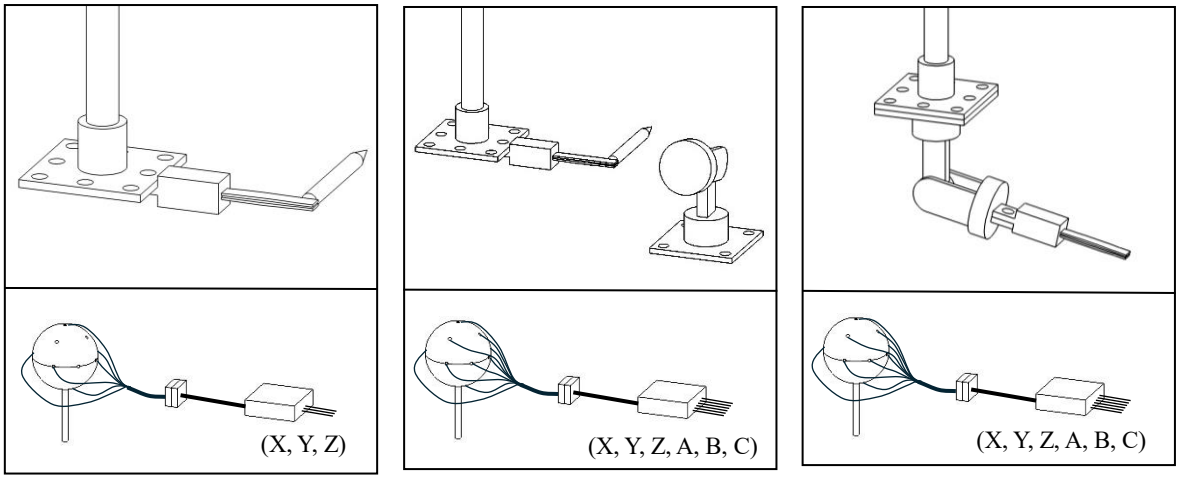
- Input Sub-system: Globe Sensor 2, Converter 3
- Output Sub-system: Frame, Block X, Motion X, Beam Y, Motion Y, Beam Z, Motion Z, Head with Interface, Toolholder Automatic Adapter, Stylus 2
- General Product Adaptability: 0.2678



(a). The optimal original product configuration



(b). A mechanism with three rotational axes



Original Configuration *Configuration for Adaptation A* *Configuration for Adaptation B*

(c). Partial views of the original and adapted product configurations

Figure 5.12. The optimal original product configuration and its adapted configurations

5.5.2.2. Product adaptations from the original product configuration

- *Product adaptation considering adaptation requirements A*

  From the Adaptation Requirements A given in Table 5.4, a mechanism with 3 rotational axes, as shown in Figure 5.12(b), was added to the output sub-system to control the orientation of the iPad, and Globe Sensor 2 was adapted and Converter 3 was replaced by Converter 6 for the input sub-system to obtain the control signals of the 6 motions, including the 3 translational

motions in X, Y, and Z directions and the 3 rotational motions about X, Y, and Z axes. The major components in the input and output sub-systems are shown in Figure 5.12(c).

- *Product adaptation considering adaptation requirements B*

  From the Adaptation Requirements B given in Table 5.4, a mechanism with 3 rotational axes, as shown in Figure 5.12(b), was added to the output sub-system to connect the head and the toolholder to hold a fork, and Globe Sensor 2 was adapted and Converter 3 was replaced by Converter 6 for the input sub-system to obtain the control signals of the 6 motions, including the 3 translational motions in X, Y, and Z directions and the 3 rotational motions about X, Y, and Z axes. The major components in the input and output sub-systems are shown in Figure 5.12(c).

5.5.2.3. Comparative study

The optimal adaptable product design solution obtained in Section 5.5.2.1, based on the general product adaptability, was compared with the optimal traditional product design solution obtained based on total component cost. First, from the 24 solutions, the best one with the lowest total component cost was identified as:

The optimal traditional product design solution considering the total component cost:

- Input Sub-system: Block Sensor 1, Converter 1
- Output Sub-system: Frame, Block X, Motion X, Beam Y, Motion Y, Beam Z, Motion Z, Head without Interface, Toolholder 1, Stylus 1
- Total Cost: $2010

The optimal traditional product design solution with the lowest total component cost is shown in Figure 5.13.

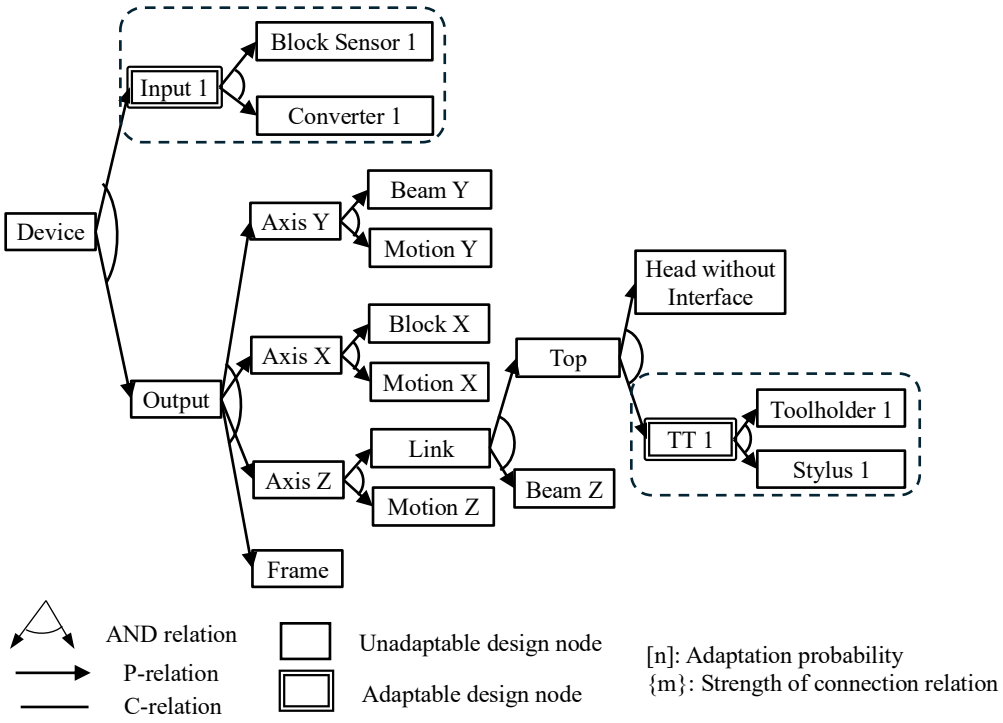


Figure 5.13. Traditional design with the best total component cost

The original product configuration was adapted considering adaptation requirements.

- *Product adaptation considering adaptation requirements A*

  From the Adaptation Requirements A given in Table 5.4, a mechanism with 3 rotational axes, as shown in Figure 5.12(b), was added to the output sub-system to control the orientation of the iPad, and the new components of Block Sensor 3 and Converter 4 were added to the input sub-system to obtain the control signals of the additional 3 rotational motions about X, Y, and Z axes.

- *Product adaptation considering adaptation requirements B*

  From the Adaptation Requirements B given in Table 5.4, a mechanism with 3 rotational axes, as shown in Figure 5.12(b), Toolholder 2, Specific Fork, and Communication Cables were added to the output sub-system, and new components of Block Sensor 3 and Converter 4 were added to the input sub-system to obtain the control signals of the additional 3 rotational motions about X, Y, and Z axes.

Comparison between the optimal adaptable product design solution obtained based on the general product adaptability and the optimal traditional product design solution obtained based on the total component cost, considering product adaptation scenarios, is shown in Table 5.6. From the results, we can see that although the total component cost of the adaptable product design for the original configuration was higher (i.e., \$2270 for the best adaptable product design and \$2010 for the best traditional product design), the component costs for its adaptations were lower (i.e., \$1090 for the best adaptable product design and \$1400 for the best traditional product design considering Adaptation Requirements A, and \$1095 for the best adaptable product design and \$1590 for the best traditional product design considering Adaptation Requirements B), and the total component costs considering both the original configuration and the adapted configuration were lower (i.e., \$3360 for the best adaptable product design and \$3410 for the best traditional product design considering Adaptation Requirements A, and \$3365 for the best adaptable product design and \$3600 for the best traditional product design considering Adaptation Requirements B). Therefore, the adaptable design method considering general product adaptability is effective in reducing the costs, considering future product adaptations.

Table 5.6. Results of comparative study for Case Study 1

Designs and Comparison		**Best Adaptable Design**	**Best Traditional Design**	**Comparison**
Original Product Configuration O	Objective Function	General Product Adaptability	Total Component Cost	
	General Product Adaptability	0.2678	0.1266	+0.1412
	Total Component Cost	\$2270	\$2010	+\$260
Adapted Product Configuration A	Adaptation Cost	\$1090	\$1400	–\$310
	Total Component Cost	\$3360	\$3410	–\$50
Adapted Product Configuration B	Adaptation Cost	\$1095	\$1590	–\$495
	Total Component Cost	\$3365	\$3600	–\$235

5.5.3. Case study 2: Design of an adaptable product with specific adaptation requirements

For this case study, both the Original Requirements O and the Adaptation Requirements A were considered for design of the original configuration and the adapted configuration of the adaptable product design. The generic product design considering all possible original configurations and adapted configurations was modelled by an AND-OR tree, as shown in Figure 5.14.

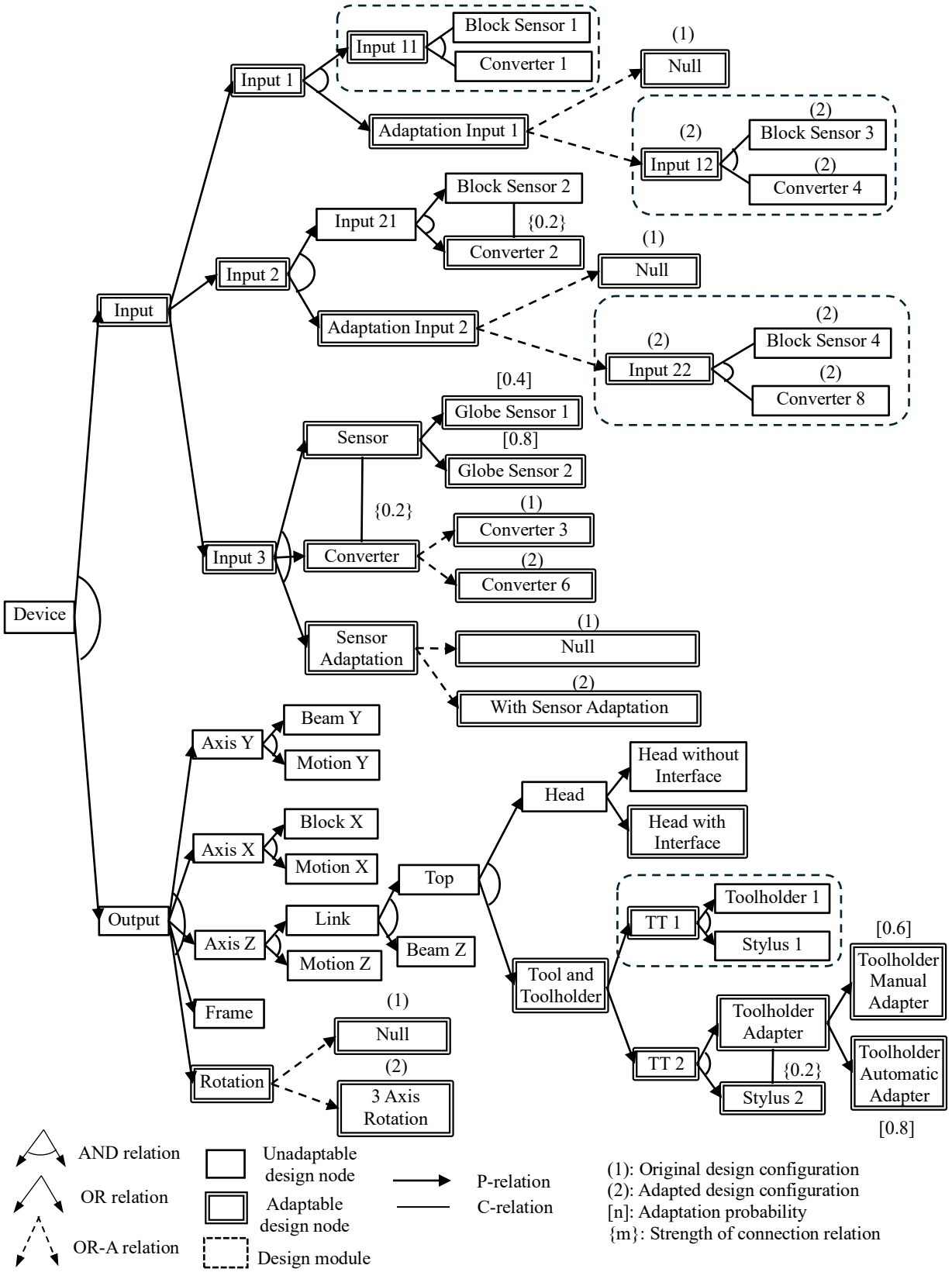


Figure 5.14. Generic AND-OR tree considering Original Requirements O and Adaptation Requirements A

From this generic AND-OR tree, 24 solutions were created through tree-based search, and each solution was defined by its original configuration and adapted configuration. By evaluating these solutions using the general product adaptability and the total component cost, respectively, the optimal adaptable product design solution and the optimal traditional product design solution were obtained, as shown in Figure 5.15 and Figure 5.16.

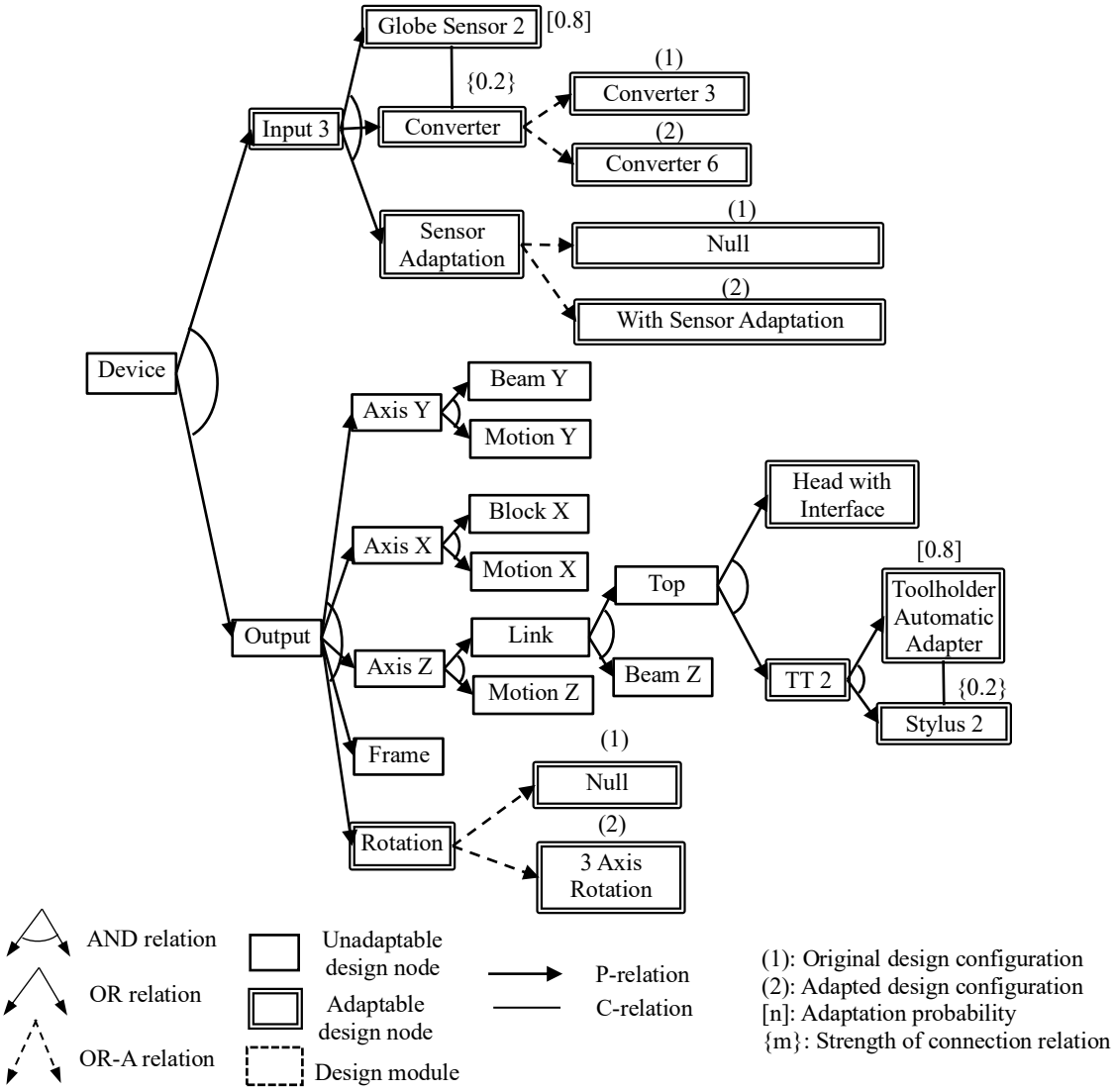


Figure 5.15. Adaptable design with the best general product adaptability

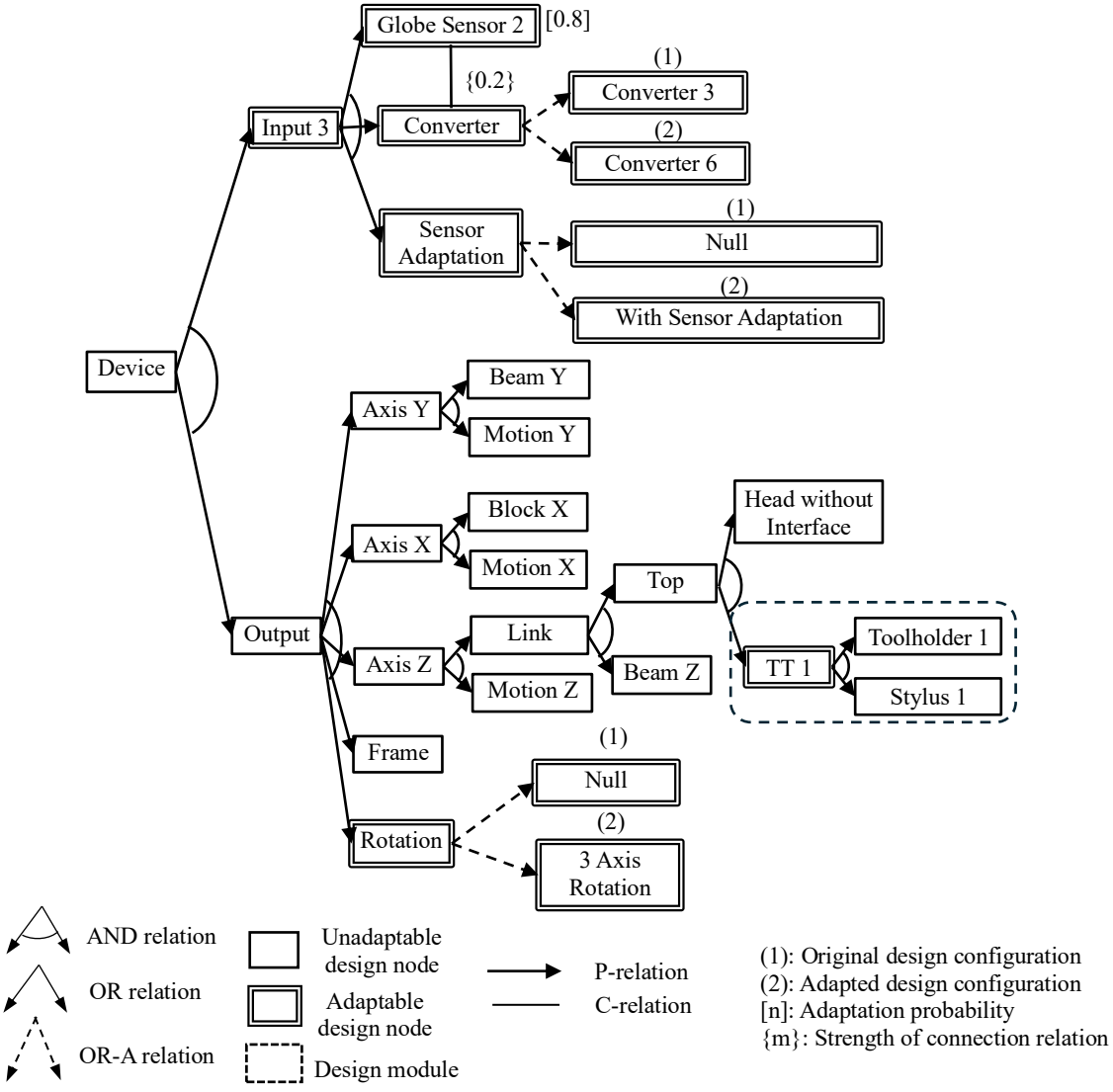


Figure 5.16. Traditional design with the best total component cost

The optimal adaptable product design solution considering the general product adaptability:

- The Original Configuration: Globe Sensor 2, Converter 3, Frame, Block X, Motion X, Beam Y, Motion Y, Beam Z, Motion Z, Head with Interface, Toolholder Automatic Adapter, Stylus 2
- The Adapted Configuration: The mechanism with 3 rotational axes was added, Globe Sensor 2 was adapted and Converter 3 was replaced by Converter 6 to obtain the control signals of the 6 translational/rotational motions.

The optimal traditional product design solution considering the total component cost:

- The Original Configuration: Globe Sensor 2, Converter 3, Frame, Block X, Motion X, Beam Y, Motion Y, Beam Z, Motion Z, Head without Interface, Toolholder 1, Stylus 1
- The Adapted Configuration: The mechanism with 3 rotational axes was added, Globe Sensor 2 was adapted and Converter 3 was replaced by Converter 6 to obtain the control signals of the 6 translational/rotational motions.

These optimal product designs were adapted based on the Adaptation Requirements B given in Table 5.4.

- *Product adaptation from the optimal adaptable product*

  The mechanism with three rotational axes was removed from the iPad support and used to connect the head with the toolholder to hold a new General Fork.

- *Product adaptation from the optimal traditional product*

  Toolholder 2, Specific Fork, and Communication Cables were added, and the mechanism with three rotational axes was removed from the iPad support and used to connect the head with the new Toolholder 2 to hold Specific Fork.

Comparison between the optimal adaptable product design solution obtained based on the general product adaptability and the optimal traditional product design solution obtained based on the total component cost, considering product adaptation scenarios, is shown in Table 5.7. From the results, we can see that even for the optimal design, considering both the original product configuration and the adapted product configuration, evaluation of the general product adaptability can be used to further improve the product adaptability (i.e., 0.2678 for the best adaptable product design and 0.2452 for the best traditional product design), considering the future known adaptation requirements. In addition, we can see that although the total component cost of the adaptable product design considering the original configuration and the adapted configuration A was higher (i.e., $3360 for the best adaptable product design and $3230 for the best traditional product design), the component cost for its adaptation to configuration B was lower (i.e., $5 for the best adaptable product design and $190 for the best traditional product design), and the total component cost considering the original configuration, the adapted configuration A, and the adapted configuration

B was lower (i.e., $3365 for the best adaptable product design and $3420 for the best traditional product design).

Table 5.7. Results of comparative study for Case Study 2

Designs and Comparison		Best Adaptable Design	Best Traditional Design	Comparison
Original Product Configuration O and Adapted Product Configuration A	Objective Function	General Product Adaptability	Total Component Cost	
	General Product Adaptability	0.2678	0.2452	+0.0226
	Total Component Cost	$3360	$3230	$130
Adapted Product Configuration B	Adaptation Cost	$5	$190	–$185
	Total Component Cost	$3365	$3420	–$55

5.6. Summary

In this research, a method to evaluate the general product adaptability considering the three influencing factors of adaptable nodes and unadaptable nodes, nodes in modules, and probabilities of node adaptations has been developed. The developed new evaluation measure has been employed in the development of a new adaptable product design approach, considering cases without or with specific requirements at the design stage for product adaptations. Case studies were developed to design an adaptable assistive device for individuals with disabilities. The general product adaptability was used to evaluate the design candidates. Effectiveness of the developed method was demonstrated by comparing the solutions achieved using the new method and the solutions obtained using the traditional design method.

Conclusions of this research are summarized as follows.

(1) Compared with the method developed by Fletcher et al. (2009), the new method to evaluate the general product adaptability works better when influencing factors of adaptable nodes and unadaptable nodes, nodes in modules, and probabilities of node adaptations are considered.

(2) By integrating the results achieved in the previous research (Martinez and Xue 2018; Saad and Xue 2024; Deabae and Xue 2025), the new adaptable product design approach is effective for modelling, evaluation and optimization considering adaptable nodes and unadaptable nodes, nodes in modules, and probabilities of node adaptations.

(3) The developed method is effective to identify the optimal design with the best general product adaptability considering both cases without specific adaptation requirements (i.e., general adaptation requirements) and cases with specific adaptation requirements for reducing the costs due to product adaptations.

Chapter 6. Conclusions and Future Work

In this chapter, the summary and contributions of the research on the optimal design of adaptable products through integrated modelling, evaluation, and optimization are presented first. The future work is then provided to discuss the challenges and research directions.

6.1. Research Summary

The objective for the design of adaptable products is to reduce the time and cost of product adaptation in the operation stages to satisfy new requirements. In this research, an approach for the design of adaptable products is developed through integrated modelling, evaluation and optimization. First, adaptation processes have been considered in addition to product design configurations for the design of adaptable products. A new method has been introduced to improve optimization efficiency for optimal design of adaptable products when large numbers of the adapted product design configuration candidates and the product adaptation process candidates are considered, as explained in Chapter 3. Second, a new approach has been developed for the design of new adaptable products, which can be easily changed during their operation stages, considering multiple alternatives of the original design configurations, the adapted design configurations, and the product adaptation processes, as explained in Chapter 4. Third, an approach has been introduced to evaluate the general product adaptability when product adaptation requirements are not given at the design stage, considering the influencing factors of adaptable and unadaptable nodes, nodes in modules, and adaptation probabilities of nodes, as explained in Chapter 5.

(1) An approach to improve optimization efficiency for the identification of the optimal adapted product design configuration and the optimal adaptation process by initial evaluation of information quality in branches of the AND-OR tree based on information entropy

In this research, a new optimization approach to identify the adapted product design configuration and the product adaptation process was developed with an initial evaluation of information quality in branches of the AND-OR tree based on information entropy. In this approach, the design of an existing product was defined by an AND tree with adaptable and unadaptable design nodes. Then, the generic design considering multiple solutions of the adapted product design after adaptation and the product adaptation process was modelled by an AND-OR tree with design and process nodes through modification of the existing product design AND tree

(e.g., addition/removal of adaptable design nodes, and addition of process nodes). Design and process nodes were further associated with design and process parameters. From the generic AND-OR tree, multiple adapted design solution candidates and adaptation process solution candidates were created through tree-based search. An evaluation scheme was then presented to evaluate both the adapted product design configurations and the product adaptation processes through multiple evaluation measures described in different units. In this evaluation method, evaluation measures were converted into comparable evaluation indices and then integrated into an overall evaluation index. Since the resulting solution space can be large when both product design candidates and adaptation process candidates are considered in the optimization process to identify the best solution, the computation efficiency has to be considered such that the optimal solution can be achieved within the required computation time period. In this research, information entropy was employed to evaluate the information quality of partial configuration/process candidates modelled as branches in the AND-OR tree to eliminate the branches that are unlikely to lead to the optimal solution for improvement of the optimization efficiency. Finally, optimization to identify the best adapted design configuration and adaptation process was conducted at two levels: configuration/process optimization level to identify the optimal adapted design configuration and the optimal adaptation process, and the parameter optimization level to identify the optimal parameter values of product configuration and adaptation process. A numerical example and an engineering application were developed to demonstrate the effectiveness of the newly introduced approach.

(2) An approach for the design of new adaptable products considering the original design configurations before adaptation, the adapted design configurations after adaptation, and the adaptation processes

In this research, a framework for the identification of the optimal original design configuration, adapted design configuration, and product adaptation process was developed to integrate both the tasks of design for adaptation of an existing product and the tasks for design of a new adaptable product into the same environment. An appropriate procedure was then developed for the design of new adaptable products, that can be easily changed during their operation stages. In this procedure, first, the generic adaptable product design considering alternative solutions of the original product design configurations, the adapted product design configurations, and the product

adaptation processes was modelled by an AND-OR tree. Nodes of this tree were defined by unadaptable design nodes, adaptable design nodes, and adaptation process nodes. Design and process nodes were further associated with design and process parameters. Design modules (i.e., a collection of grouped design nodes) were also considered in the AND-OR tree. Sub-nodes of a super-node were associated with three types of relations: AND relation, OR relation, and OR-A relation. From the generic AND-OR tree, multiple original design solution candidates, adapted design solution candidates, and adaptation process solution candidates were created through tree-based search. Each solution with a specific original design configuration, a specific adapted design configuration, and a specific adaptation process was further defined by its parameters, including parameters for the original design configuration, parameters for the adapted design configuration, and parameters for the adaptation process. Then, multiple evaluation measures, such as performance and cost, were used to evaluate each solution candidate. Similar to the previous research, these evaluation measures were converted into comparable evaluation indices and then integrated into an overall evaluation index. Finally, the optimal solution with the original design configuration, the adapted design configuration, the adaptation process, and configuration/process parameters was obtained through the two-level optimization (i.e., configuration/process optimization and parameter optimization) method. This new method was employed for the design of an adaptable vehicle for easy conversion from its ICE configuration to its EV configuration.

(3) An approach to evaluate the general product adaptability for the design of adaptable products considering influencing factors

The objective of this research was to improve the method for evaluating the general product adaptability developed in the literature by considering various factors that influence the general product adaptability. In this method, in addition to the general product adaptability defined by comparison between the actual product architecture and its ideal segregated product architecture, influences of adaptable and unadaptable components/sub-assemblies, components/sub-assemblies in modules, and uncertainties of components/sub-assemblies in product adaptation were also considered for evaluation of the general product adaptability. In this method, first, the design solution with the actual product architecture was modelled primarily by a tree with AND relations. In this tree, each node was associated with its cost percentage, representing its importance in the whole product. The relations between two nodes were classified into two categories: P-relations

and C-relations. When C-relations were considered, the actual product architecture was defined by a graph. From the actual product architecture, an ideal segregated product architecture, representing an ideal adaptable product, was created by converting all the unadaptable nodes into adaptable nodes with adaptation probabilities assigned as 1s, deleting modules, and deleting the C-relations. Then, the method to calculate the general product adaptability considering the actual product architecture and the ideal segregated product architecture was developed. The developed new evaluation measure has been employed in the development of a new adaptable product design approach, considering cases without or with specific requirements for product adaptations at the design stage. In this research, the modelling scheme developed previously for the design of new adaptable products has been improved by considering the three factors in product modelling: (1) adaptable nodes and unadaptable nodes, (2) nodes in modules, and (3) probabilities of node adaptations. The generic product, considering all possible original design configurations and adapted design configurations, was modelled by an AND-OR tree with connection relations. Design nodes were classified into adaptable nodes and unadaptable nodes. The adaptable nodes were associated with adaptation probabilities between 0 and 1. Nodes in modules were also considered. Tree-based search was used to create the original design configuration candidates and the adapted design configuration candidates. Design solutions were evaluated using the developed general product adaptability measure for the identification of the best solution. Case studies have also been implemented for the design of an adaptable device, considering cases without or with specific product adaptation requirements.

6.2. Research Contributions

The overall contribution of this research is the development of an approach for adaptable product design through integrated modelling, evaluation, and optimization.

The contributions of the developed approach are in the following three aspects.

- A method to improve optimization efficiency for identification of the optimal adapted product design and the optimal product adaptation process by initial evaluation of information quality in branches of the AND-OR tree based on information entropy

- A method for the design of new adaptable products considering the original design configurations before adaptation, the adapted design configurations after adaptation, and the adaptation processes
- A method to evaluate the general product adaptability by considering various factors that influence the general product adaptability for the design of adaptable products

(1) A new method to improve optimization efficiency for identification of the optimal adapted product design configuration and the optimal product adaptation process by initial evaluation of information quality in branches of the AND-OR tree based on information entropy

As discussed in Chapter 2, in the existing methods for modelling, evaluation, and optimization for the design of adaptable products, only product configurations were considered to identify the optimal design solutions. However, efforts required for adaptation processes can also have significant influence on the overall cost of product adaptation. When both design solution candidates and adaptation process candidates are considered for the design of an adaptable product, the size of the solution space may grow significantly, and the optimization efficiency needs to be improved. To overcome these limitations, a new method to improve optimization efficiency has been developed for the identification of the optimal adapted design configuration and the optimal product adaptation process by initial evaluation of information quality in branches of the AND-OR tree based on information entropy.

The contributions of this research are summarized as follows.

- The product adaptation process has been considered for the first time in addition to the design of the adaptable products.
- Information entropy has been used to evaluate information quality in branches of the AND-OR tree for improving optimization efficiency by pruning the branches with less useful information.
- Methods to calculate information entropy of AND-OR tree have been developed through studies on the relations among entropy measures of nodes with AND relations and OR relations in the AND-OR tree.
- A systematic procedure for adaptation of an existing product has been developed for the identification of the optimal adapted design and its adaptation process considering multiple

candidates of the product configurations, the adaptation processes, and the parameters of configuration/process.

(2) A new method for the design of new adaptable products considering the original design configurations before adaptation, the adapted design configurations after adaptation, and the adaptation processes

In the current methods of adaptable product design, the tasks for adaptation of existing products and the tasks for the design of new adaptable products that can be easily changed during their utilization stages have never been integrated in the same environment. There is also a lack of a systematic procedure for the design of new adaptable products. To overcome these limitations, a new method has been developed for the design of new adaptable products considering the original design configurations before adaptation, the adapted design configurations after adaptation, and the adaptation processes.

The contributions of this research are summarized as follows.

- A framework has been developed to integrate the tasks for adaptation of existing products and the tasks for the design of new adaptable products in the same environment.
- A modelling scheme has been developed to describe different candidates for the original product configurations, the adapted product configurations, the adaptation processes, and the configuration/process parameters using an AND-OR tree.
- A systematic procedure has been developed for the identification of the optimal solution with the original design configuration, the adapted design configuration, the adaptation process, and the configuration/process parameters for the design of a new adaptable product.

(3) A method to evaluate the general product adaptability by considering various factors that influence the general product adaptability for the design of adaptable products

In many cases, adaptation requirements may not be given during the design stage. General product adaptability is a measure to evaluate product adaptability without given product adaptation requirements. In the general product adaptability approach introduced in the literature (Fletcher et al. 2009), key factors that can significantly influence the general product adaptability have not been considered. To overcome these limitations, a method has been developed in this thesis to

improve the general product adaptability measure developed by Fletcher et al. (2009) considering the influences of adaptable and unadaptable components/sub-assemblies, components/sub-assemblies in modules, and uncertainties of components/sub-assemblies in product adaptation.

The contributions of this research are summarized as follows.

- A method has been developed to define the AND tree of the actual product architecture considering adaptable design nodes and unadaptable design nodes, design nodes in modules, and adaptation probabilities of design nodes. A method to define the ideal segregated product architecture AND tree has also been developed.
- A modelling method has been developed to define the generic product AND-OR tree with multiple solution candidates considering adaptable design nodes and unadaptable design nodes, design nodes in modules, and adaptation probabilities of design nodes.
- A method has been developed to evaluate the general product adaptability of a design candidate solution considering the influence of adaptable and unadaptable nodes, design nodes in modules, and adaptation probabilities of design nodes.
- A systematic procedure has been developed for the identification of the optimal adaptable product design with the best general product adaptability considering the influence of adaptable and unadaptable nodes, design nodes in modules, and adaptation probabilities of design nodes, considering cases without specific adaptation requirements and cases with specific adaptation requirements for reducing the costs due to product adaptations.

6.3. Future Work

Despite the effectiveness of the developed approach for the design of adaptable products through integrated modelling, evaluation, and optimization, a number of issues need to be further addressed in our future research. The major issues are summarized as follows.

(1) Development of industrial applications using the developed approach is required

While the effectiveness of the proposed methods in this research was validated through case studies, further work is required to demonstrate their effectiveness in real-world industrial applications. Industrial products such as vehicles, consumer electronics, and large-scale machinery

involve thousands of components, multiple adaptation possibilities, and complex lifecycle constraints. Applying the developed approaches to such products would verify the practicality of the developed methods and highlight potential challenges in data availability, computational efficiency, and integration with existing design workflows. By developing full-scale industrial applications, the research can move beyond academic case studies to establish tangible benefits in cost reduction, product longevity, and sustainable engineering practices.

(2) An effective computer environment is needed for the optimal design of adaptable products

The methods proposed in this thesis provide theoretical foundations for modelling, evaluation, and optimization in adaptable product design. However, their practical applications would benefit greatly from the development of a dedicated computer environment that integrates these methods into a user-friendly and computationally efficient system. In this system, both product configurations and adaptation processes should be considered, enabling designers to model complex systems, generate design and process alternatives, and evaluate the product adaptability measures seamlessly.

Future work should therefore focus on implementing the AND-OR tree modelling method, adaptability evaluation measures, and multi-level optimization models into a comprehensive software tool. Ideally, this environment should be compatible with the existing computer-aided design (CAD) and product lifecycle management (PLM) systems. Additional features such as automated branch pruning based on the information entropy method, and integration of multi-objective trade-offs (e.g., cost vs. performance, adaptability vs. complexity) would further enhance the usability of the software tools. Such a computer environment would serve as a bridge between the theoretical methods developed in this thesis and their large-scale deployment in industrial design practice.

(3) Product adaptations across multiple lifecycle stages should be considered

In this research, product adaptation was primarily modelled as a single conversion from an original design configuration to an adapted design configuration. However, in real-world practice, products may undergo multiple successive adaptations over their lifecycle as technologies, customer needs, and regulations continue to evolve.

Future work should therefore focus on developing methods of modelling, evaluation, and optimization for product adaptation across multiple stages of a product's lifespan. Such an approach would not only evaluate the cost and feasibility of a single adaptation but also anticipate how one adaptation influences future adaptation opportunities. Replacing a major module in the first adaptation may either enable or constrain later changes. For instance, when converting an ICE car into an EV, the designer may choose to replace the fuel tank with a fixed battery pack that exactly fits into the existing tank space. If the battery pack is designed with modular slots or standardized connections, the car can be adapted again later by upgrading to higher-capacity batteries or swapping in new battery technologies. If the battery is permanently fixed and custom-shaped only for the initial conversion, future upgrades become very difficult.

By extending the developed methods to capture sequential product adaptations, designers could identify long-term strategies that maximize product adaptability across the entire lifecycle, ensuring sustained competitiveness of products in rapidly changing markets.

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