Hierarchical Modularization and Dual-Domain Formation for Product Adaptability

By

Yunhui Liu

A thesis submitted to
the Faculty of Graduate Studies
in partial fulfilment of
the requirements for the degree of
Master of Science

Department of Mechanical Engineering
University of Manitoba
Winnipeg, Manitoba

Jan 2017

Abstract

Product adaptability is the capability to adjust a product by adding/replacing its constituents for different applications. To acquire this capability, a product should be a modular structure that can form different modular combinations. The purpose of this thesis is proposing a design method to develop such products. The method includes the following characteristics: a product essentially implements its applications by providing proper actions/reactions to interact with its surrounding conditions; such actions/reactions can be used to develop the subsystems of a product by building energy-flow or force-path connections; optional modules can be separated from the subsystems that contain optional applications; all modules are arranged as an open architecture to provide space and interface for each optional module; and each module is endued with the principal content of actions/reactions, inside energy flows or force paths, space, and interfaces constraints, so that it can be physically formed through a dual-domain formation process. Following this method, a multi-purpose electric vehicle (MEV) is developed. Adaptability Efficacy (AE) is proposed to evaluate the effectiveness of the proposed method.

Acknowledgments

I would like to take this opportunity to thank my advisor, Dr. Qingjin Peng. Without his constant support and great patience, I would not be able to complete this thesis. His encouragement and advice are very important for me to complete my degree.

This research is supported by the Discovery Grants from the Natural Sciences and Engineering Research Council (NSERC) of Canada and GETS Grant from the University of Manitoba.

Dedication

Dedicated to my father Zhaoyan Liu

and my mother Guilan Wang

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Background

Adaptable Design (AD) develops a product that can evolve in its lifetime so that existing technical resources can be reused for different applications. By this means, the repetitive waste in product design and manufacture can be eliminated. Such diversification-based reutilization distinguishes AD from other similar design theories such as the modular design, product platform/family design, mass customization design, and reconfiguration design.

The objective of AD is the product adaptability. For customers, product adaptability means that a product can be easily upgraded by adding/replacing its constituents for different applications. For manufacturers, it means that different products can share the same components to save time and investment. A typical example of product adaptability is PC. On the one hand, computer components, such as monitors, CPUs, keyboards, and memory cards, can be upgraded in their lifetime; on the other hand, these components can be shared by different manufacturers. However, because of the complexity and rigidity of mechanical parts and components, AD has been a challenging topic for the mechanical design since its introduction (Gu, 2004, 2009).

Product adaptability can be met using optional modules, common interfaces and adjustable product architectures. For example, a hand tool kit shown in Figure 1.1 has the following characteristics: 1) optional function units such as handles, rods, joints, socket heads, wrenches and bits; 2) common connection joints; and 3) multiple combination configurations. By these means, the hand tool kit can meet different applications; therefore, it can replace many individual wrenches and screwdrivers. In this example, the re-utilization of handles, rods, joints, socket heads, wrenches and bits provides diverse functional applications with a low cost.

Figure 1.1: Hand tool kit (http://wujin.3158.cn/20130116/n488688279264.html)

AD has become increasingly meaningful for mechanical design because of the following reasons:

1. With the widespread application of intelligent manufacturing and new materials, engineers have more freedom to fabricate parts and components. For example, CNC and 3D printing can form complex geometric parts easily. This enables a product or a module to be developed with specific geometric profiles.
2. More and more mechanical components are provided as professional units to perform specialized functions such as linear and rotary actuators, serve-motors, and reducers, etc. The adoption of these units deeply affects the mechanical design.

3. Today's manufacturers face a dilemma. On the one hand, they wish to maximize the production of a product to save investment; on the other hand, customers ask for a wide variety of products in a smaller volume to meet diverse requirements.
4. The reutilization of parts and components becomes an important consideration for the environmental protection by reducing the waste created in the disposal or recycling process of discarded products.

1.2 Problem Statement and Research Objectives

Existing research activities have successfully explored the properties of AD, including the adaptable module, interface, architecture and adaptability evaluation. Some design methods have been proposed to develop adaptable products, such as tree-based, network-based, AND–OR graph-based, and axiomatic design-based methods. However, they are not sufficient to support AD because of the following reasons:

1. The existing modularization method of AD is mainly based on the axiomatic design. It is difficult to develop uncoupled and decoupled relations between decomposed functional requirements and their physical designs when a product involves large variables. This made the axiomatic design based modularization hard to apply in practical work.
2. Open architecture can favor the implementation of product adaptability. However, the method to form the open architecture including overall arranging, interface fitting, and module forming is still under research.

Based on these problems, this thesis proposes a method to develop adaptable products so that the product adaptability can be implemented effectively.

Product adaptability has been classified as specific and general adaptability depending on whether the adaptability is predictable to develop an adaptable product initially (Gu, 2004, 2009). Since the specific adaptability directly relates to customer requirements and determines the development of an adaptable product, this thesis considers the specific adaptability as the product adaptability.

To simplify the process, some typical systems in mechanical design, such as the hydraulic system, pneumatic system, electric system, and thermal system, will not be considered in this study because they are relatively independent and highly adaptable within the product. This thesis will focus on the systems involving the mechanical energy conversion, motion and force transmission in mechanical design.

1.3 Thesis Outline

This thesis has six chapters. Chapter 1 introduces the background of AD, its existing problems, and the objective of this research. Chapter 2 is the literature review. Chapter 3 proposes a seven-step design method using the hierarchical modularization and dual-domain formation. Chapter 4 applies the proposed method to develop a multi-purpose electric vehicle (MEV). Chapter 5 proposes a set of evaluation criteria. Chapter 6 outlines conclusions and future research.

Chapter 2

Literature Review

This chapter reviews the existing theories, research and methodologies relating to adaptable design.

2.1 Function and Modelling

The mechanical design is converting an intended need into functions, and then to form physical models to realize a product.

2.1.1 Function

The mechanical design starts from functions that come from customer requirements. Based on the FBS (Function-Behaviour-Structure) model, a function is the design intention, purpose and result of an artefact's behaviour (Gero, 2004; Vermaas at el, 2007). Ulrich (1995) explains that a function is what a product does to what its physical characteristics are. Stone and Wood (2000) described the function as "verb-object". Depending on the occurrence of variant, the functions of an intended design can be classified as basic, special, auxiliary and adaptive types (Pahl et al, 2007); or simply classified into compulsory and optional types (Li, 2007). To represent an intended design effectively, Axiomatic Design suggests a set of minimum independent functions (Suh, 2001). These statements show that the function is a concept to describe the abstract expectation of physical products. However, comparing with standardized physical concepts such as the weight, volume, pressure and speed, the function is still an ambiguous description. It cannot provide repeatability as the function is not based on an objective criterion. It works for the common mechanical design when functions are explicit and generally accepted. But for Adaptable Design, it may become a shortage when dealing with complicate functions. At this point, the function requires a precise interpretation to serve as a design indicator.

Sometimes the "performance" is used to specify how well a product to implement a function, such as the speed, power, life, efficiency, vibration and others. For the performance, Ulrich (1995) classifies it as the local performance and global performance. The local performance arises only from physical properties of the local region of a product, and the global performance reflect overall product's size, shape, mass and material properties. But the performance is only used as a supplementary for the function; itself is not a sufficient design indicator to represent an intended design.

2.1.2 Function Modelling and Design Modelling

Function modelling is to represent an intended design by organizing involved function elements. Design modelling is to create a physical product from the function modelling. In the literature, there are two approaches for the function and design modelling. One is functional "flow"; the other is the hierarchical decomposition.

The functional "flow" approach considers an overall product as a black box with the physical "flows" such as the energy, material and signal that either entry or exit of the black box. Customer requirements, such as the operation, control, electricity, torque and motion can be converted into such flows. Then, the flows create a series of sub-functions chains, which may transform, diverge or converge into other flows. Finally, all sub-function chains are organized and aggregated to form a complete functional model (Otto et al, 1998; Stone et al, 2000).

For the decomposition approach, Axiomatic Design proposes a method called zigzag mapping between a function domain and a physical domain. For each function, the physical domain conceives a design concept. Then the function is decomposed into a set of the minimum independent sub-functions. Step-by-step, the decomposition keeps going until all conceived concepts become producible design characteristics. During the decomposition process, the decomposed function elements should one-to-one map their corresponding producible design characteristics either uncoupled or decoupled through a design matrix. Meanwhile, the selection of producible design characteristics should meet the information axiom to ensure the design solution (Suh, 2001).

Comparing above two methods, the functional "flow" approach can well describe relations and interactions between sub-functions of a product or a product family, but it does not provide details to create and organize sub-functions, and it does not mention how to transform sub-functions into producible design characteristics. The hierarchical decomposition approach can well connect decomposed function elements with producible design characteristics, but it easily causes a lot of design diversity that increases design difficulties.

The process from function modelling to design modelling is to transform functional elements into physical design characteristics. Two methodologies have been used for this task as shown in Figure 2.1. One is "mapping" (Suh, 2001), the other is "FBS (Function–Behaviour-Structure) modelling" (Gero, 2004; Vermaas at el, 2007; Beek at el, 2010; Cascini et al, 2011).

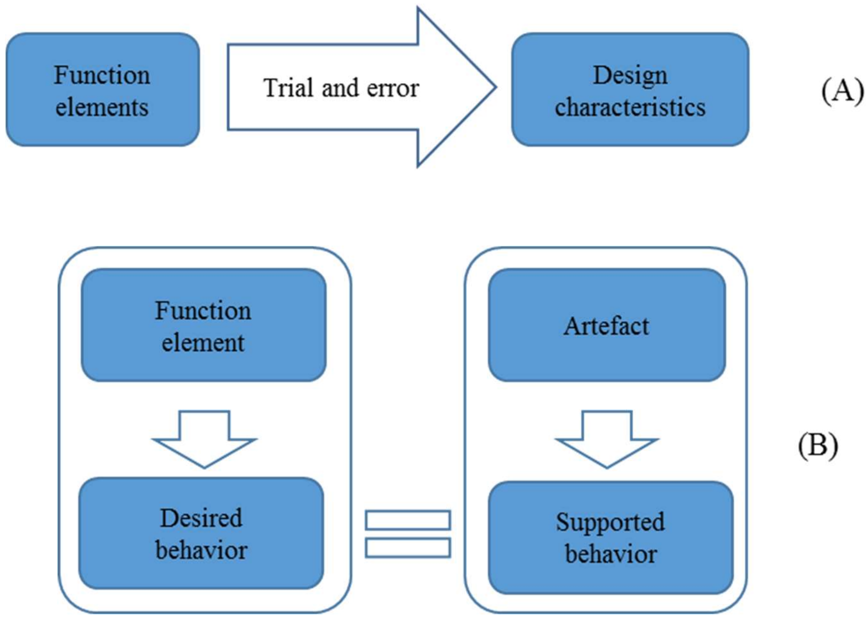


Figure 2.1: Mapping (A) and FBS model (B)

The mapping method has been applied by Axiomatic Design. It directly matches functions and design characteristics through the trial and error until every design characteristic one-to-one matches its function elements. This method often causes the extra work. The FBS model matches a function element and an artefact through the criterion of "behaviour". It recognizes that a function is achieved by a particularly behaviour, and the behaviour is caused by an artefact. When two behaviours are coincident, the definition of the function and artefact can be considered to match each other. This method can effectively reduce the matching deviation. However, the behaviour is a rough concept that may affect matching accuracy. Both methods are still lack of repeatability to perform their work.

At a higher level from function modelling to design modelling, Clark & Fujitmoto (1991) introduced the product integrity as a goal to guide the involved deign. Product integrity includes the internal integrity and external integrity. The internal integrity refers to the consistency between the product function and its structure, whereas the external integrity refers to the consistency between the product performance and customer's expectations.

2.2 Product Structure

Product structure is the interactive pattern and organization of physical components to implement functions. A typical product structure includes the integral structure and modular structure.

2.2.1 Integral Structure

The integral structure is a single product "block" to implement all function requirements. It is hard to identify boundaries within a product as sometime boundaries even do not exist. The demanded performance of an intended design can affect the choice of its structure (Yin et al, 2012; Höltä et al, 2005). The integral structure is often used to optimize the product performance, using some key performance characteristics such as the speed and efficiency that are closely related to the size, shape and weight of most products (Huang, 2000).

Main design techniques of the integral structure are function sharing and geometric nesting. Function sharing integrates several neighbouring parts or components into a single physical piece. A part or component always has secondary and incidental properties such as force-support materials with respect to its intended function. By recognizing and exploiting these secondary properties, neighbouring parts or components can be eliminated if their functions can share a consolidated physical piece, so that redundant physical properties of parts and components can be eliminated to minimize the size and mass of a product (Ulrich, 1995). Geometric nesting interleaves and arranges the geometric profiles of components so that they can occupy the minimum volume with a desired shape. Function sharing and geometric nesting can help forming a highly compact design with the desired profile and interface. However, geometric nesting inevitably incurs interface coupling among inside components. It makes the integral structure hard to adjust for function variety (Yin et al, 2012).

2.2.2 Modular Structure

Modular structure breaks a product structure into discrete modules, so that the product can fully function with interchangeable modules through well-defined interfaces (Eager et al, 2010; Simpson et al, 2013). Modular structure makes it possible to increase product feasibility, variety, and durability by replacing, upgrading using add-on modules without affecting other parts of products.

Architecture, module and interface are three basic characteristics of the modular structure. The architecture is the combination pattern of modules. The module is an independent physical block corresponding to its function elements, and standardized based on the physical and functional similarity and a set of connecting interfaces (Huang, 2000). Miller & Elgard (1998) explained that the difference between a simple block and a module relies on if they can realize a specific function. The interface is a physical connection between modules to achieve functional interactions (Li, 2007), or a port that logically or physically integrates boundaries between systems or boundaries between systems and their environment (Rahmani et al, 2012).

Comparing with the integral structure, the modular structure decreases function sharing, incurring the redundant physical expense such as the interface, more parts and suboptimal use of the space, mass and energy. The highest performance based standardization also causes the excessive capability for each individual application. In short, the integral architecture favours the "technical performance", and the modular architecture favours the "business performance" (Hölttä et al, 2005). AD is essentially the modular structure (Gu, 2009). It emphasizes the product adaptability (Janthong et al, 2009; Levandowski et al, 2015).

2.2.3 Hybrid Structure

Most products use somewhat a hybrid structure. Fixson and Park (2008) used two dimensions of the "function-component allocation" and "interface" to measure the difference between the integral and modular structure. Hölttä et al (2005) used Singular Value Modularity Index (SMI) to analyze the trade-off between the integral and modular architecture by analyzing three typical architectures including the fully integral, bus-modular, and fully modular. Their research shows that restrict technical constraints lead to a high degree of the integral structure, otherwise products tend to the modularization. Yin et al (2012) analyzed the cost and possible benefits from the integration of function modules by taking account of System Integrator (SI) and Heavy System Integrator (HSI) considering the product performance. They got three corollaries including 1) there is no single structure that is optimal in all cases, whereas there are always sub-optimal architectures; 2) for global performance, the modular structure is an sub-optimal choice; 3) to obtain the global performance, the integral architecture is always an optimal option.

2.3 Product Adaptability

Adaptable Design (AD) research is mainly for the product adaptability. Previously Axiomatic Design has the similar consideration to deal with large flexible systems. A large flexible system is a system that has many functions with corresponding design characteristics. Within the system, only a random subset of functions with their physical characteristics is required at any time or circumstance so that the system has adaptability (Suh, 2001). However, Axiomatic Design does not mention how to form such systems. Current research shows that the product adaptability comes from the adaptable architecture, module and interface. This section will review research in these aspects.

2.3.1 Architecture

There are mainly four factors that influences the architecture, including the market variance, usage variance, technology change and design for X (production, supply and lifecycle criteria) (Dahmus et al, 2001). The architecture may relate to the task definition of a firm and industry structure (Foss, 1998). The interface strategy of product development also affects the architecture (Chen et al, 2005). Inevitably, AD should consider these factors when forming the adaptable architecture.

Since AD uses the modular structure, its architecture will follow a manner of the modular combination. In this aspect, two basic combination modes are suggested based on interface connections as shown in Figure 2.2. One is the "Hamburger" (A); the other is the "Base Unit" (B) (Eggen, 2003).

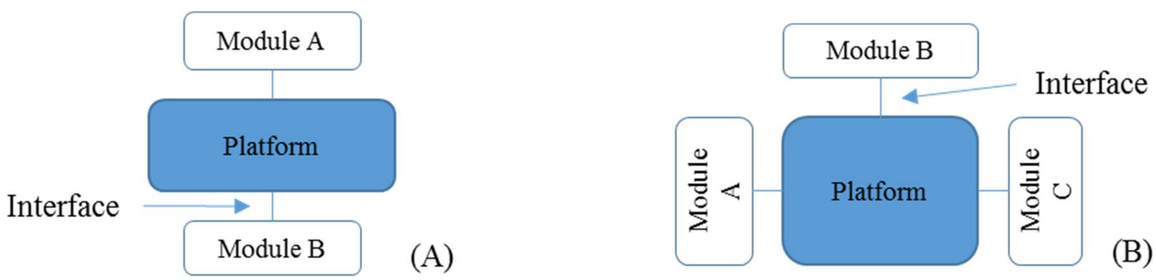


Figure 2.2: "Hamburger" (A) and "Base Unit" assembly (B)

Similarly, Hölttä et al (2005) suggested two typical combination modes of modules depending on the spatial sequence and interface conditions. One is the "fully modular", in which each module only connects to its direct neighbours; the other is the "bus-modular", in which all modules are connected to a common base/platform. Two combination modes can grow and blend to form more complex modular combinations.

Specific to AD, an important requirement is that when any module is adjusted, it only affects its downward sub-functions. At this point, Hashemian (2005) proposed "the rational functional structure" and Fletcher (2007) proposed "the segregate product architecture" as the ideal adaptable architecture (Figure 2.3). Within the architecture, any downward functional elements only interact with its upward functional elements without affecting the other parts of a product. Peng et al propose an Open-Architecture Product (OAP) with public interfaces to expand the product variety (Peng et al, 2013). OAP is characterized as the common platform, customized modules and user personal components.

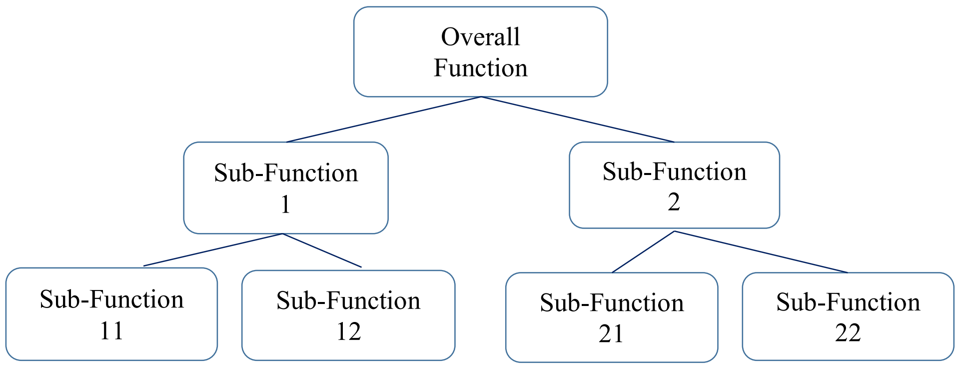


Figure 2.3: Segregated architecture

2.3.2 Module and Interface

Module and interface form a conjugate pair to form a modular product. Stone et al (2001) proposed a heuristic method to form modules and interfaces based on sequential and parallel function chains following the material, signal and energy "flows". The method includes three heuristics: 1) a set of function elements on the dominant flow defines a module from where the flow entries a system to where the flow either exits the system or converts within the system; 2) each limb of a parallel function chain identifies a module at the flow's branch point; 3) the conversion-transmission flow defines a module. Dahmus et al (2001) suggested a portfolio architecting method on a product family to define shared modules and unique modules depending on the commonality of related function modules Hölttä and Wood (2005) determined modular boundaries using the "design effort complexity metric", which quantitatively presents the effort to redesign a product when the "flows" change. They defined interfaces where the "design effort complexity metric" is low between two "function cores". The independence axiom of Axiomatic Design can guide modularization because formed modules should be functional and physical uncoupled. In this aspect, Cheng et al (2012) developed a cluster manner to form the module group. Wang et al (2015) used the design matrix of Axiomatic Design to define modules called M-set, by which the effort of modification in the conceptual stage can be reduced. Besides these, clustering of component-based Design Structure Matrices (DSMs) can also be used to identify and define modules and their interfaces (Helmer et al, 2008; Beek et al, 2010).

For the interface, Li (2007) classified interfaces into 3 categories: 1) slot: each of the interfaces is different from the others, and different modules cannot be interchanged; 2) bus: a standard interface accepts different modules with the same type of interfaces; 3) sectional: no common platform, modules can connect each other via identical interfaces. Gu (2003) proposed a special interface connector called Mechbus to connect add-on modules and the platform. The Mechbus works like a converter, consisting of a base and a connector. The base is mounted on a platform and the connector attaches add-on modules. It facilitates the design of modules and platforms. Chen and Liu (2005) used a concept "openness" to evaluate the interface, which represents the sharing level of related recourses. Their research shows that the standardization of interfaces can benefit products improvement, but meanwhile set the upper limits for the improvement. Because of this reason, they gave different strategies for interfaces. Fletcher (2007) analyzed interfaces in terms of physical interface/interaction factors to evaluate the general product adaptability. Hu et al (2014) proposed "Interface Efficacy" to evaluate the interface efficiency by integrating the interface graph representation, criteria matrix, and house of quality.

2.4 Adaptable Design Evaluation

The AD evaluation has been proposed based on different aspects. One method is to evaluate the product adaptability as specific product adaptability and general product adaptability. The specific product adaptability is the product adaptability predicted under the design consideration. It can be evaluated by the comparison of the effort of product adaption with respect to the effort of new product creation (Gu et al, 2009). Li (2007) evaluated the specific adaptability through the extendibility of functions, upgradeability of modules, and customizability of components; the extendibility of functions considers the potential function extension; the upgradeability of modules considered the product improvement; and the customizability of components considered the personal convenience of product adaption. Measurements of three aspects are then normalized and combined as the specific product adaptability. The general product adaptability is the product adaptability that is not considered initially. It is evaluated by comparing the actual or "full" architecture of a product with its ideal form of the "segregated" architecture. It is quantitatively measured based on the characteristic parameters of interfaces and interactions (Fletcher, 2007).

Recently, Cheng et al (2011) evaluated the product adaptability using the essential adaptability and behaviour adaptability. The essential adaptability reflects the effort such as time, resource and energy to modify a current product for new function requirements. The easier the modification is; the better the essential adaptability has. The behaviour adaptability reflects the customer's satisfaction of adapted products. It shows the cost-effective level of the adaptation activity. Their research is suitable to determine if an adaptation is proper for a product or not. An adaptation should be implemented when both essential adaptability and behaviour adaptability are high. At three adaptable levels of the product, modules and parts, Peng (2014) proposed “Design efficiency” to evaluate the implementation of adaptability considering three major factors of product architecture, complexity of interface, and operation ability. Zhang (2014, 2015) applied “robustness” to evaluate AD. He considered adaptable activities that may happen at three levels: the parameter, configuration and architecture. For each level, he proposed methods to model design candidates and calculated their robustness, so that an optimal design candidate can be identified with the best robustness.

These research solutions have made a significant progress in the AD evaluation. Design methods have been proposed to develop adaptable products, such as tree-based, network-based, AND–OR graph-based, and axiomatic design-based methods (Gu et al, 2009). However, they are not sufficient to support some requirements of adaptable products. The method to form the open architecture products including overall arranging, interface fitting, and module forming is still under research.

2.5 Summary

The common practice of mechanical design starts at expressing customer requirements as a set of functions to represent an intended design. By the functional “flow “or hierarchical decomposition, these functions are decomposed into function elements so that each function element can be implemented by a design characteristic either by the “mapping” or “FBS model”. All design characteristics then form a design model for the intended design. The function model and design model can be organized as integral and modular structures. The integral structure uses function sharing and geometric nesting to form highly compact products and modules. Modular structure uses modules and interfaces to improve the product flexibility. Adaptable Design is based on the modular structure. It acquires the product adaptability using the adaptable architecture, modules and interfaces. Related to this research, there are following problems found in literature:

1. The concept of product functions requires an accurate and precise description.
2. The relation between function elements and design characteristics including “mapping” and “FBS (Function–Behaviour-Structure) model” needs a rigorous match.
3. A systematic design method to form the open architecture products is required for the AD.

This research will propose solutions for these problems in following chapters.

Chapter 3

Proposed Design Method

This chapter proposes a design method for Adaptable Design. This method is developed based on the following two general facts:

1. The purpose of mechanical design is satisfying the requirements of customers using a product.
2. The nature of design is combining different elements for intended purposes using systematic integration.

Fact 1 shows that mechanical design is a form of transformation from customer requirements to a physical product. Fact 2 indicates that the transformation is achieved by the combination of mechanical elements following mechanical principles. Therefore, transformation and combination are two basic means of mechanical design. Based on this thinking, Section 3.1 first introduces the concepts of design transformation and dual-domain combination, and then develops the methods for dual-domain formation; Section 3.2 introduces the process of hierarchical modularization; Section 3.3 develops a seven-step design method of AD.

3.1 Transformation and Dual-Domain Formation

Considering the transformation and combination as two basic means of mechanical design, this section develops a set of concepts and methods for the mechanical design. Section 3.1.1 introduces the concept of design transformation; Section 3.1.2 introduces the concept of dual-domain combination; Section 3.1.3 develops the methods for dual-domain formation.

3.1.1 Design Transformation

The purpose of mechanical design is transforming customer requirements into mechanical products. This is achieved by converting original engineering recourses such as electricity, fuel, and materials into utilizable forms. In physics, such conversion follows mechanical principles through organized energy/force operations, which include: energy conversion such as electromagnetic conversion; energy transmission such as motion transmission; and force transmission such as force linkage. A product provides required physical conditions for organized energy/force operations by combining mechanical units and mechanical characteristics. The mechanical units are components such as fasteners, bearings, gearboxes, motors, and hydraulic and pneumatic components from professional suppliers. The mechanical characteristics are producible "shape-material" that usually can be formed by the manufacturer itself. Here, the "shape" is a geometric profile such as a flat plane or a cylindrical surface; the "material" is a physical substance such as metal, rubber, or plastic. The mechanical characteristics are usually used in design to form a part. For example, two parallel planes and two coaxial cylindrical surfaces of copper can form a bushing. For this reason, although the minimum element of a product is each part, the mechanical units and mechanical characteristics are considered as elements of the mechanical design.

The mechanical elements can support specific energy/force operations. For example, an electric motor converts electricity into rotation motion; a shaft transmits the rotation motion; and a bolt connects two parts together by the compression force. Combined mechanical elements can therefore support combined energy/force operations. Through the combined energy/force operations, original engineering resources can be converted into utilizable forms. By this means, a product can be developed to meet customer requirements. For example, an electric car can run on a road by electricity through the combinative conversion as shown in Figure 3.1.

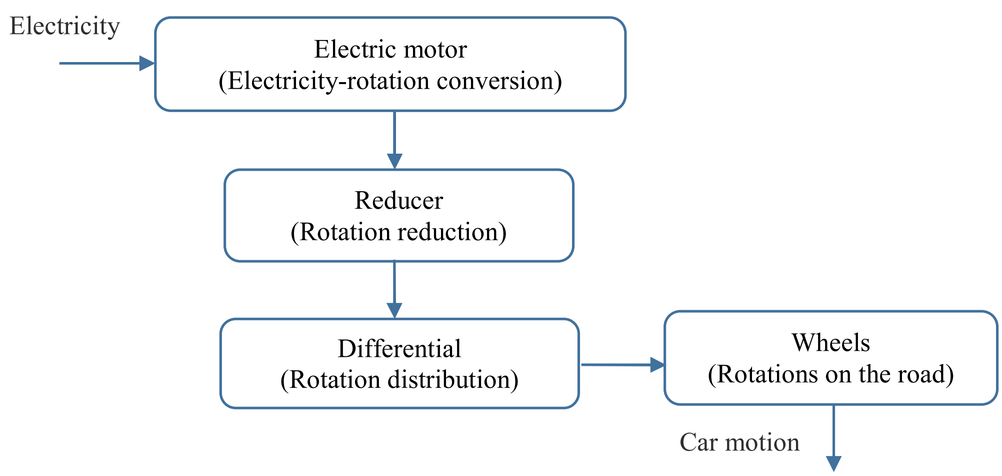


Figure 3.1: Power train of an electric vehicle

Considering this, finding a mechanical element for an energy/force action is critical to transforming customer requirements into a product. As mentioned in Chapter 2, many researchers had similar concerns. "Mapping" (Suh, 2010) and the "FBS (Function–Behaviour-Structure) Model" (Gero, 2004, 2015) are two typical methods that have been applied to process such work. However, they do not effectively generate a consistent solution. Based on the law of energy conservation and Newton's law, an energy/force operation is meaningful when it can interact with its surrounding conditions explained in the form of energy/force actions/reactions. Specifically, an energy operation can accept input energy and provide required output energy; a force operation can statically or dynamically support surrounding forces. Therefore, this thesis proposes the concept of design transformation as shown in Figure 3.2.

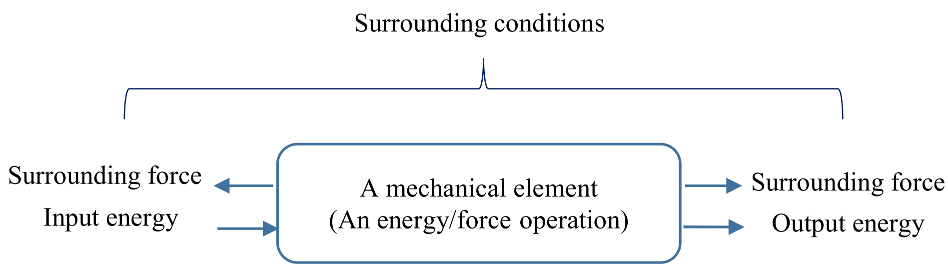


Figure 3.2: Design transformation

This design transformation includes two steps. The first step deduces the surrounding conditions to be interacted; the second step develops the energy/force operation that can be implemented by a mechanical element to interact with the surrounding conditions. For example, to reduce the rotation between a motor and a shaft, the first step finds the torque/rpm from the motor and the torque/rpm to drive the shaft; the second step develops the rotation deduction system that can be implemented by the gearbox to meet conditions of the motor and shaft. To fix a gearbox on a chassis, the first step determines the forces acting on the gearbox such as weight and input/output torques; the second step develops the support-constraints implemented by the mounting devices for the gearbox. Furthermore, since the real purpose of design transformation is interacting with the surrounding conditions, an energy/force operation can be replaced by a set of combinative operations implemented by a set of combinative mechanical elements if they can interact with the same surrounding conditions. Therefore, the design transformation method can also be applied to develop a set of combinative mechanical elements for the surrounding conditions. This explains that mechanical design is a form of transformation when a set of combinative mechanical elements forms a product.

Ideally, a mechanical element or a set of combinative mechanical elements that supports the most efficient energy flow or the shortest force path is preferred. However, technology and cost limitations such as the manufacturing methods, required performances, components from suppliers, and the investments will limit the development of mechanical elements. Although it is possible to develop different mechanical elements for the same surrounding conditions, only the solution that best fit these limitations can be selected. For this reason, a consistent design solution can be developed to reduce the design diversity and uncertainty.

As for the surrounding conditions, they usually are neighbour factors within a product. When the design transformation is applied to develop a product, the surrounding conditions come from its external factors such as the application, operation, power supply, and environmental disturbance. In design practice, very often the relations between a product and these factors are expressed as overall functions. The overall functions should be converted into surrounding conditions to use the proposed transformation method. This thinking borrows ideas from the "Black Box" model (Stone et al, 2001), which consider a product as a "Black Box" and expresses overall functions as energy flows into or exit the

"Black Box." The conversion from overall functions to the surrounding conditions will be introduced in Section 3.2.

3.1.2 Dual-Domain Combination

Based on the discussion in Section 3.1.1, the energy/force operations are interactively combined to interact with its surrounding conditions and the mechanical elements are physically combined as a complete product. Therefore, the development of a product should consider two kinds of combinations. One is the interactive combination of energy/force operations; the other is the physical combination of mechanical elements. For this reason, this thesis proposes a principal domain and a physical domain to process two combinations.

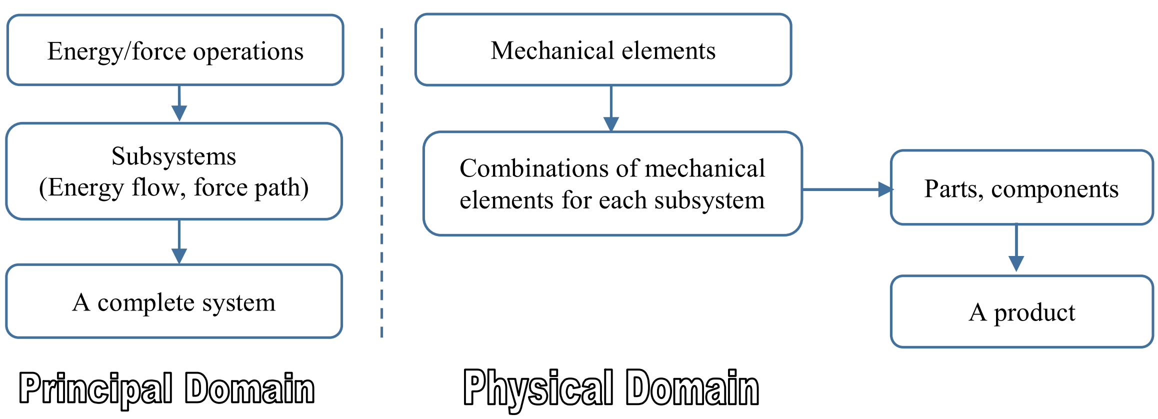


Figure 3.3: Combination in the principal and physical domain

As shown in Figure 3.3, in the principal domain (left), the energy/force operations are first combined as energy flows and force paths to form a set of subsystems, and then the subsystems are combined as a complete system; in the physical domain (right), the mechanical elements are first combined to support each subsystem, and then successively integrated into a product. Therefore, two models are built for an intended design. One is the principal model of energy/force operations to interact with the surrounding conditions; the other is the physical model of mechanical elements to be a mechanical entity. For example, Figure 3.4 shows the two models of a two-speed gearbox. The left one is its principal model; the right one is its physical model. Although only the physical model is presented to users, both models are required for the design process.

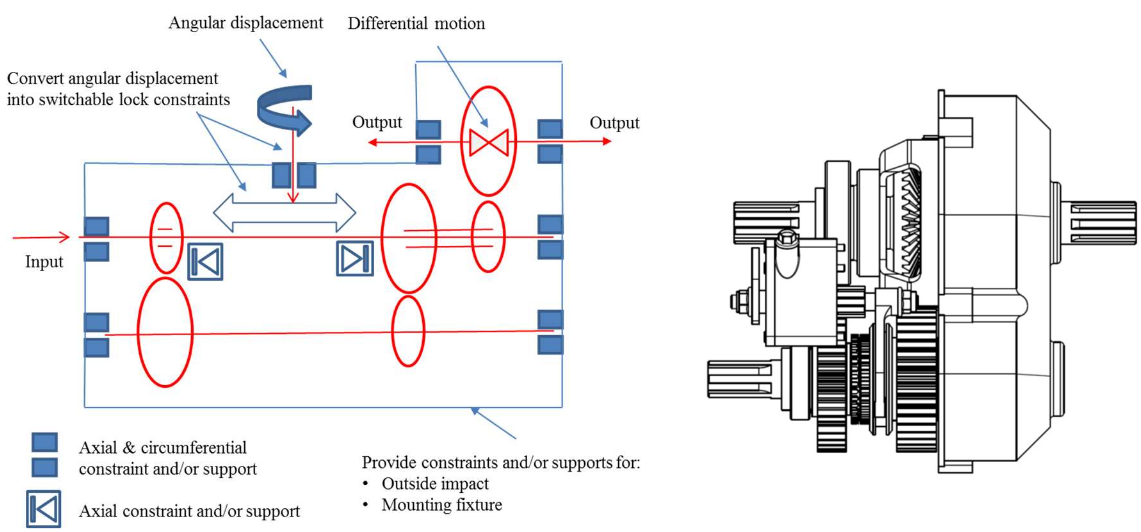


Figure 3.4: Principal model (left) and physical model (right)

The principal model is not as same as the functional model mentioned in Chapter 2. The principal model consists of energy/force operations, whereas the functional model consists of the conceptual descriptions of function elements. For example, Stone et al. (2001) use a verb-object form to express the content of a function element. Since the concepts used for energy/force expression such as speed, mass, and thermal energy have been scientifically developed, the principal model can give an accurate and precise discerption qualitatively and quantitively.

The principal model and physical model should be coincident with each other because they present the same product in a different manner. For this reason, the combinations of mechanical elements and their energy/force operations should be transformable at every combinative status.

3.1.3 Dual-domain Formation

Based on the introduction of dual-domain combination, the formation of a product can be considered as a process to find mechanical elements implementing the energy/force operations for required surrounding conditions. Since the energy/force operations are first combined as subsystems and then form a complete system, the formation of a product can be organized at a subsystem-level and at an element-level. The subsystem-level develops subsystems to interact with related surrounding conditions; the element-level first develops mechanical elements for the energy/force operations of each subsystem, and then combines them respectively into a complete system (the principal model) and a product (physical model).

The development of subsystems includes developing a force-path subsystem to support surrounding forces and developing an energy-flow subsystem to accept input energy and provide required output energy. Ideally, the most efficient energy flow or the shortest force path is preferred under technology and cost limitations. For this reason, this study proposes two ways to form the subsystems.

1. An energy-flow subsystem should be developed with the most efficient energy flows to accept input energy and provide required output energy.

2. A force-path subsystem should be developed with the shortest force paths to balance the surrounding forces either statically or dynamically.

By this means, each subsystem of a product is independently developed as the best solution, it will serve as a datum for the design at the element-level. Generally, a product may have a set of surrounding forces and different sets of input/output energies. Thus, a force-path subsystem and a set of energy-flow subsystems can be developed for the product.

There are two stages of design at the element-level. The first stage transforms each subsystem into mechanical elements along the energy flows and force paths; the second stage successively integrates the mechanical elements into a product. At the first stage, the mechanical elements for a subsystem usually cannot be developed at once because they have different priorities. This can be explained by the following reasons:

1. Since the purpose of design transformation is interacting with the surrounding conditions, the mechanical elements that directly interact with the surrounding conditions dominate the other mechanical elements within a subsystem.
2. Mechanical elements may have different restrictions that affect the selection of relevant mechanical elements. Usually the mechanical elements that have more restrictions should be considered preferentially. For example, the mechanical elements that support the conversion, divergence, or convergence of energy flows usually dominate the mechanical elements that support the transmission of energy flows within an energy-flow subsystem.
3. More and more professional mechanical components have been developed for specific applications such as electric motor, differential, and ball joint. These mechanical elements can be selected instead of redesigning them.

For these reasons, this thesis proposes a transformation process to transform a subsystem into mechanical elements. Figure 3.5 shows the process applied for an energy-flow subsystem; Figure 3.6. shows the process applied for a force-path subsystem.

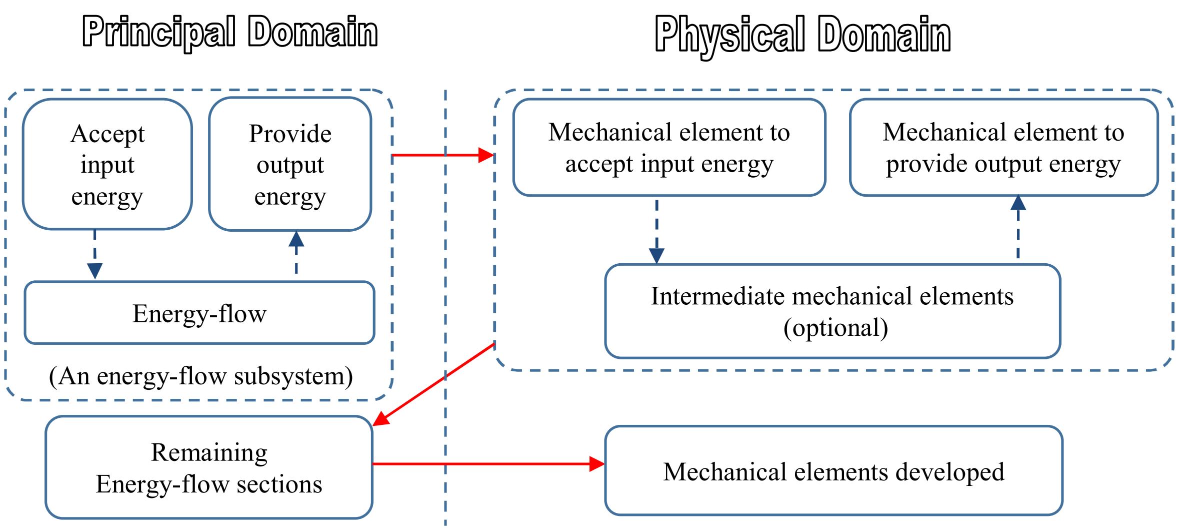


Figure 3.5: Transformation process for the energy-flow subsystem

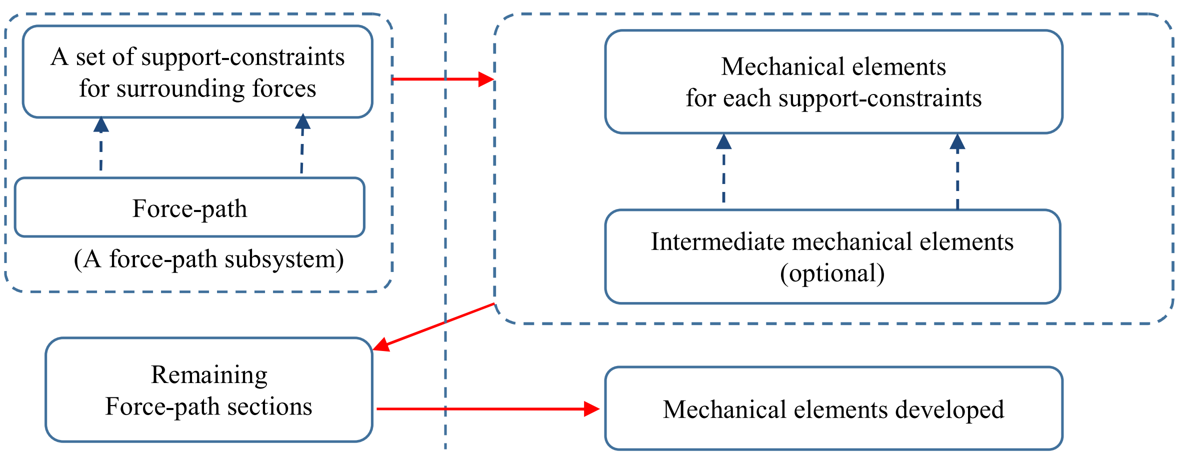


Figure 3.6: Transformation process for the force-path subsystem

The process includes four steps. Its two applications are explained in detail as follows:

1. The process starts from the principal domain, in which an energy-flow subsystem or a force-path subsystem is assigned.

2. Going to the physical domain, this step develops mechanical elements to accept input energy and provide output energy for the energy-flow subsystem, or develops mechanical elements to support each surrounding force for the force-path subsystem. Sometimes this step may develop some mechanical elements that should be considered preferentially.
3. Back to the principal domain, based on the mechanical elements developed in Step 2, this step distinguishes the remaining sections of energy flows or force paths that are not transformed yet.
4. Switching to the physical domain, this step transforms the remaining sections of energy flows or force paths in Step 3 into mechanical elements so that the subsystem can be completely transformed. Sometimes if an section needs a set of unknown mechanical elements, it can be considered as the sub-subsystem and back to Step 1 to restart the process until the subsystem is completely transformed.

Through this process, an energy-flow or force-path subsystem is decomposed into transformable sections, which are essentially energy/force operations implemented by their mechanical elements. It is possible to develop different mechanical elements for a subsystem. As mentioned, the solution that best fit technology and cost limitations can be selected.

At the second stage, in the principal domain, the subsystems are further combined into a system under the following considerations:

1. Operations of the subsystems should not disturb each other. Energy flows or force paths can be adjusted to avoid the system interference caused by the combination.

2. A force-path subsystem should provide support-constraints for energy-flow subsystems. This is because the energy-flow subsystems are supported and constrained by the force-path subsystem to form a product.

In the physical domain, the mechanical elements are integrated into a product. When integrating them together, the limitation of materials and manufacture methods will inevitably cause conflicts, such as the interference and un-matching. There are two flexibilities enabling such combinations as follows:

1. Each energy-force operation may have different mechanical elements. It is possible to select a proper one so that all mechanical elements can fit together. For example, a bearing seat can have different profiles for different fixtures.
2. The energy flows and force paths can be adjusted to enlarge the selection of mechanical elements. For example, a straight tube can be bent to avoid a spatial interference.

In both situations, each original subsystem is distorted to develop the overall optimized solution of a product. For this reason, each original subsystem can serve as a datum providing the reference for overall optimization.

3.2 Hierarchical Modularization

Based on the discussion in Section 3.1, surrounding conditions determine an intended design. However, the relevant information for a design is customer requirements; surrounding conditions are unknown. The customer requirements should be converted into the surrounding conditions to develop a product. For adaptable products, the customer requirements also should be converted into surrounding conditions to develop a set of modules since customer requirements are met by combinations of different modules. For this reason, Section 3.2.1 introduces the conversion from customer requirements to the surrounding conditions to derive the required action/reactions. Section 3.2.2 introduces the modularization based on the derived action/reactions.

3.2.1 Hierarchical Actions/Reactions

Customer requirements, such as the conceptual description, vague demands, and operational manners that reflect relations between a product and its surroundings, are generally classified as overall functions to determine an intended design. Since this thesis uses surrounding conditions to determine an intended design, the overall functions are considered as basic and auxiliary functions to convert customer requirements into surrounding conditions.

The basic function refers to the desired effects caused by actions of a product interacting with its physical object. For example, the object of a shear machine is sheet metal, and the desired effect is shearing the sheet metal into pieces; objects of a mini electric car are a driver and loads, and the desired effect is transiting the driver and loads on a road. Sometimes a product may have multiple objects and cause compound effects. The basic function develops initial basic surrounding conditions resulting in the required actions/reactions of a product. Around its implementation, other basic surrounding conditions can be developed resulting in other required actions/reactions of the product. This thesis proposes the following process for this work:

1. Since the desired effects are caused by the actions of a product, the product should provide support-constraints and proper forms of output energy to interact with its object. Meanwhile, the product is supported by its surrounding environment, it should provide support-constraints to interact with the surrounding environment.
2. A product requires power supply such as electricity, fuel, or labour. A product is operated/controlled for its application by proper inputs such as human-machine interactions. These factors can be considered as different forms of input energy. A product should provide reactions to accept them.

The auxiliary function refers to the reaction required to deal with disturbances that affect the implementation of basic function adversely, i.e. the disturbances may affect objects of a product and derived actions/reactions. The disturbances are essentially energy/force actions. They develop the secondary surrounding conditions of a product. A product should adopt proper reactions to reduce/eliminate their negative effects. Generally, a product can adopt two types of reactions. One is hard support-constraint by force reacting; the other is soft support-constraint by energy converting. A car, for example, can use the hard support-constraint of a roof to stop rain, or it can use the soft support-constraint by converting road bumping into spring energy to have a smooth driving.

Finally, a set of actions/reactions can be derived through this process, which are classified as the support-constraints for surrounding forces and the actions/reactions for surrounding input-output energies. They conceptually express an intended design even when its inside structure is still unknown. Here, one thing should be mentioned is that this process may develop different actions/reactions for the same surrounding conditions, resulting in different design solutions. Since the comparison of design solutions is not the main concern of this thesis, this thesis will find a solution based on the technology and cost comparison as follows:

1. A design concept can be selected if it can effectively implement basic and auxiliary function, but other concepts cannot.
2. If there are several design concepts that can effectively implement basic and auxiliary function, the one that has the lowest cost is selected.

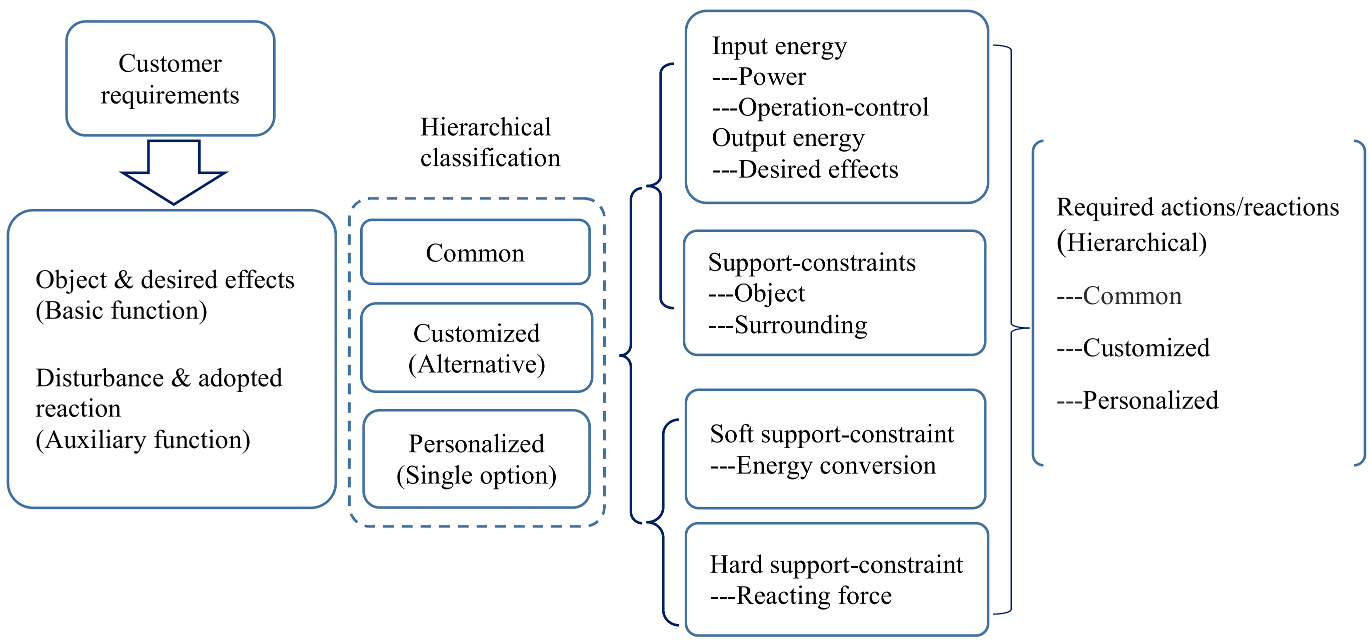


Figure 3.7: Derivation of required actions/reactions

Generally, the objects, desired effects, and disturbances are constant factors or only vary in a certain range when considering a normal product. However, they can vary significantly for an adaptable product because it will be adjusted for a large range of applications. This develops multiple sets of basic and auxiliary functions for these applications. With respect to these applications, some functions are commonly required, some functions are selected alternatively, and some functions are single options. These functions have been hierarchically classified as common, customized, and personalized functions hierarchically (Peng, 2013). For this reason, this thesis classifies the objects, desired effects, and disturbances as common, customized, and personalized types to derive the required actions/reactions that can be classified as common, customized, and personalized types correspondingly (see Figure 3.7).

Overall, this work develops a set of hierarchical actions/reactions. As discussed in Section 3.1, these actions/reactions are connected by energy flows and force paths, so they should be at the ends of energy flows or force paths. Since they are hierarchically selected for optional applications, any low-level actions/reaction should be added at the end of an energy flow or a force path developed from its up-level action/reaction. Considering the ideal functional architecture of AD is the segregated architecture, which asks any downward functional elements only to interact with its upward functional elements, the energy flows or force paths connecting optional actions/reactions should "branch out" independently. To represent their relations visually, this thesis proposes an explosion diagram as shown in Figure 3.8 as follows:

1. The common actions/reactions form a central basis to add the actions/reactions of each optional application successively based on their functional relations. Each branch contains one optional application with its the actions/reactions.
2. The customized optional applications with their actions/reactions are neighboured by an "or" and added on the basis or its upward actions/reactions by sharing one interacting point.

3. The personalized application with its the actions/reactions will be added on the basis or its upward actions/reactions at one interacting point.

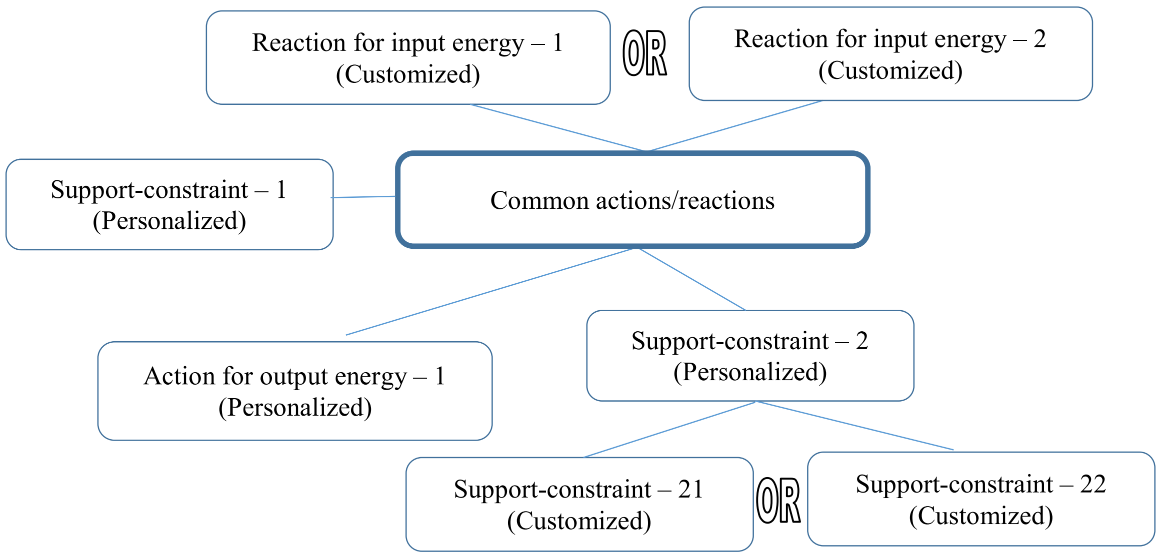


Figure 3.8: Explosion diagram of required actions/reactions

The diagram shows an open architecture in the view of energy/force operations. No matter how complex an adaptable product forms its physical structure, its actions/reactions relations should present such an architectural form. Therefore, the formation of explosion diagram is a prerequisite to form a physical open architecture.

3.2.2 Modularization

AD forms a set of modules under an open architecture with adaptable interfaces so that they can form combinations for different applications (Peng, 2013). Therefore, all derived actions/reactions should be modularized under this requirement. This thesis proposes a modularization process including the following three steps:

1. Optional modules distinguishing
2. Subsystems forming and interface setting

3. Overall arranging and interface planning

First, as mentioned in Chapter 2, a modular structure causes redundant physical expense such as more parts and the excessive capability of each individual application. Therefore, the least number of modules is preferred if related customer requirements can be satisfied. For this reason, each optional application with its actions/reactions determines a module, which can be identified using Figure 3.8.

Second, this step first connects related actions/reactions to form subsystems and then sets up interfaces to separate optional modules from them. Since the optional actions/reactions are supported by their subsystems and the purpose of AD is reusing existing technical resources, the optional portion of a subsystem should be separated by an interface to keep the rest portion reusable. Furthermore, the connection/disconnection of an interface should be simple to favor assembly/disassembly operations. For these reasons, the optional modules can be separated from the subsystems along energy flows and force paths by the following methods:

1. For customized subsystems, the first step is to identify their common portion and then set up interfaces where the subsystems are separable and have the simplest interactions in energy flows and force paths. Sometimes the subsystems should be adjusted to make a reusable portion with a common shared interface.
2. For a personalized subsystem, interfaces can be set where the subsystem is separable and has the simplest interactions in energy flows and force paths.

For an easy approach, the interface setting can start from the “branches” connecting the basis as shown in Figure 3.8, and then spread to the outside branches. By this means, this step separates each optional module by setting the simplest interface interactions. For the common portions of the subsystems, it is better to form a platform for them; otherwise, the least modules are searched if they are separated by other modules or required by other factors such as maintenance, assembly, and transportation.

Third, module adding/replacing is physically limited by the space allowance and interface fitting. To acquire the space allowance, all modules should be arranged as an open architecture to provide a room/space accessible for every optional module. For the interface fitting, since modules are under development, interfaces can be planned as certain mechanical forms for the modules to follow. The main considerations of interface fitting are the interface alignment, fastening, interface interaction transmission, and assembly/disassembly operation. Some simple and common forms are preferred because they have less constraints for adaptability. For this reason, the interface in a force path prefers a flat/strip plane fastened with alignment devices to limit the six-degree freedom; the interface in an energy flow prefers some professional connections, such as a pair of spline shaft/housing to transmit rotation, and hydraulic fittings to transmit oil. If interfaces do not allow these choices, then specialized forms should be developed.

Through this work, this section develops and assigns the principal content of actions/reactions, interfaces, space constraints, and inside energy flows or force paths to each module. Based on this information, each module can be formed through the dual-domain formation process introduced in Section 3.1.

3.3 Proposed Design Method for Adaptable Design

Based on the discussion in Sections 3.1 and 3.2, a design method is proposed as shown in Figure 3.9, including seven steps for the modularization and module integration.

Step 1: Customer Requirements

This step gathers the relevant information of an intended design from customers.

Step 2: Basic/auxiliary functions & required actions/reactions

This step converts customer requirements into surrounding conditions by considering customer requirements as basic and auxiliary functions. From the basic functions, basic support-constraints can be developed by considering the force interactions between a product and its object and surrounding environment; the actions/reactions for input-output energies can be developed by considering the actions of the product to its object, and power supply and operation-control of the product. For the auxiliary functions, auxiliary support-constraints including hard and soft support-constraints can be developed based on the disturbances that will affect actions/reactions of the basic function adversely.

Step 3: Explosion diagram & optional modules

This step forms the explosion diagram of derived actions/reactions to express their functional relations. In the diagram, common actions/reactions form a central basis; the actions/reactions for optional applications are successively added around the basis based on functional relations. Each optional application identifies an optional module. The central basis can be temporarily considered as a common module.

Step 4: Subsystem building and interface setting

This step first develops subsystems to connect related actions/reactions. The actions/reactions for input and output energies are connected by the shortest energy flows; support-constraints for surrounding forces are balanced statically/dynamically by the shortest force paths. Then optional modules are separated from these subsystems by setting interfaces where the energy flows and force paths are separable to have the minimum interactions. The common portions can form a platform, or the least modules if they have to be separated.

Step 5: Overall arranging & interface planning

This step arranges all modules to acquire room/spaces for every optional module, meanwhile plans certain mechanical forms of interfaces for the modules to follow.

After these steps, each module is assigned by the principal content of actions/reactions, interfaces, profile constraints and inside energy flows or force paths. Then each module can be formed by the two following steps.

Step 6: Mechanical element transformation

This step transforms each subsystem within a module into the mechanical elements along energy flows and force paths by the dual-domain transformation process.

Step 7: Subsystem combination & mechanical element integration

This step combines the subsystems as a complete system (the principal model), and integrates the mechanical elements into a module (the physical model). In the principal domain, the subsystems are further combined as a complete system without conflicts; a force-path subsystem should provide support-constraints for the energy-flow subsystems. In the physical domain, the mechanical elements are integrated into a complete module.

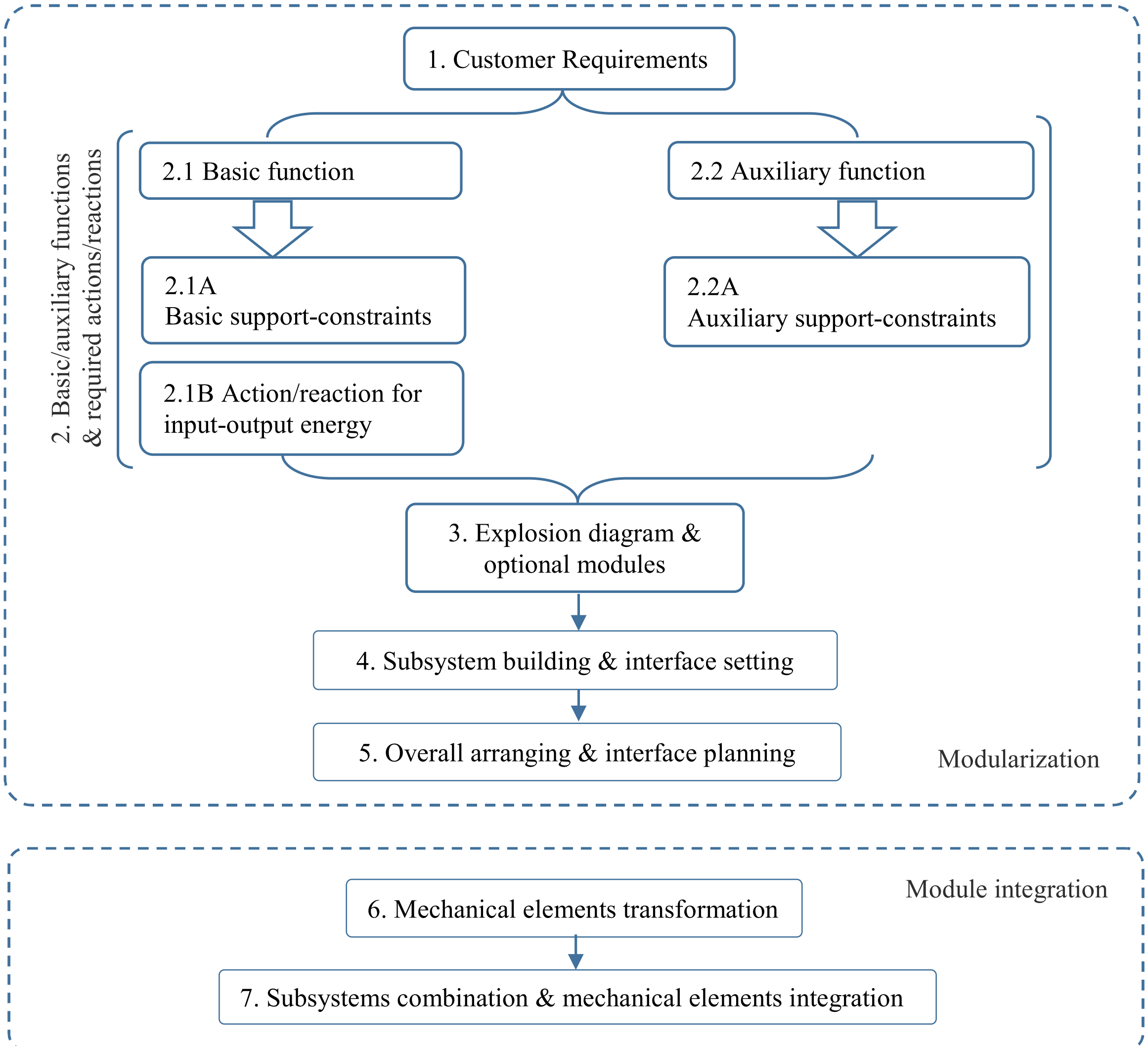


Figure 3.9: Proposed design method for AD

Chapter 4

Applications of the Proposed Method

Multiple-purpose electric vehicle (MEV) is a low-cost handy transportation tool. MEV can be used by small businesses and families for commuting, shopping and delivering. They can also be used in industrial facilities, recreation areas and parks for the short distance transportation. Previously a MEV model has been developed using a normal vehicle design method as shown in Figure 4.1. Limited by its traditional structure, it only provides the product adaptabilities of adding a windshield and a roof successively. The investigation of customers shows that some people wish to get steering wheel option, and some people wish to get different trunks to carry different loads. To provide these adaptabilities, this chapter will use the proposed design method to develop a new MEV model.

Figure 4.1: Previous MEV

4.1 Hierarchical Modularization

Following the procedure introduced in Section 3.3 from step 1 to step 5, this section derives the required actions/reactions from customer requirements, modularizes the derived actions/reactions, and endues each module with the principal content of actions/reactions, interfaces, profile constraints and inside energy flows or force paths.

Step 1: Customer requirements

The relevant information of MEV is gathered from customers and summarized as follows.

1. A driver can carry bulk loads or packing boxes;
2. The driver uses a foot to control the acceleration and brake;
3. Customers wish to have handle bar or steering wheel options;
4. It can be charged by home or public electric sources;
5. It runs on common road conditions;
6. It has options to use in sunny, rainy or windy weather.

Step 2.1: Basic function

Based on the items 1 and 5 of customer requirements, the MEV has one common object (a driver) and two customised objects (bulk loads or packing boxes). These objects have a common desired effect to be moved on a road. This initially develops basic surrounding conditions of the MEV.

Step 2.1A: Basic support-constraints

To implement the basic functions, the MEV should provide the support-constraint for a driver and for the bulk loads or packing boxes. Besides this, the MEV should be supported on a road for moving. Commonly the MEV can have two plans for this purpose. One is a three-wheel plan; the other is a four-wheel plan. This design chooses the four-wheel plan because technically it can provide an even load distribution, better dynamic stability and safety.

Step 2.1B: Action/reaction for input-output energy

The motion of MEV can be considered as a form of output energy. To move on a road, the MEV can use the front-wheel steering with front-wheel or rear-wheel driving through the rotation of wheels, which can be accelerated/decelerated to speed or slow the vehicle. This design chooses rear-wheel driving by comparing them technically and costly as follows:

1. Although front-wheel driving can provide more usable room/space for a gas car, rear-wheel driving MEV can possess the same advantage because it does not need the components of a gas car such as a radiator, a filter, a manifold, and a complex transmission.
2. One reason to adopt front-wheel driving is to get good cooling conditions for a gas engine. This is unnecessary for an electric motor because of its energy conversion principles.
3. Front-wheel driving is more complex and expensive because it requires special transmission components including constant-velocity universal joints and spindles. The components of rear-wheel driving can be simple to save cost.

The input energies of MEV come from the items 2, 3, and 4 of customer requirements that are also basic surrounding conditions. The MEV should provide reactions to accept these input energies. These contents are explained as follows:

1. The power supply of MEV is home and public electric charge. Since the electric charge is standardized, this is a common form of input energy. The MEV should provide an inlet to accept the electric charge.
2. The operation-controls of MEV includes common requirements of the foot acceleration and brake, and customized options of a handlebar or a steering wheel. They are essentially position displacements or angular displacements operated by a driver. The MEV should provide reactions to accept these input motions.

These contents are summarized in Table 4.1.

Table 4.1: Basic surrounding conditions & required actions/reactions

Basic surrounding conditions		**Required Actions/reactions**
Objects	A driver	Support-constraints for a driver
	Bulk loads	Support-constraints for bulk loads
	Packing boxes	Support-constraints for packing boxes
Desired effects	To be moved on a road	Driving rotations/steering deflections Rotation accelerates/decelerates
Surrounding environment	Road	Four-wheel contacts on a road
Operation & control	Handle bar steering	To accept angular displacement (±angle)
	Steering wheel steering	To accept angular displacement (±turn)
	Foot acceleration	To accept position displacement
	Foot brake	To accept position displacement
Power supply	home/public electric charge	To accept electric charge

Step 2.2: Auxiliary functions

Based on the items 5 and 6 of customer requirements, the MEV have the secondary surrounding conditions of road and weather disturbances affecting the implementation of basic function adversely. Proper reactions should be adapted to reduce/eliminate their negative effects. These contents are explained as follows:

1. Common road conditions can cause uneven impacts to the wheels affecting the motion of a vehicle. To reduce their affections, the wheels should be movable vertically to have a smooth driving.
2. Wind can affect a driver and rain can affect bulk loads. The MEV requires a windproof and a rainproof to eliminate their negative effects. They are personalized reactions because customers only require them for specific applications.

Step 2.2A: Auxiliary support-constraints

This step converts the disturbances/reactions into auxiliary support-constraints as follows:

1. The disturbance of road conditions is essentially impact energy. The MEV can convert the impact energy into spring energy by the elastic deformation.
2. Wind is airflow. The MEV can use a hard constraint to guide the airflow.
3. Rain is water drops. The MEV can use a hard constraint to block them.

These contents are summarized in Table 4.2.

Table 4.2: Secondary surrounding conditions & auxiliary support-constraints

Auxiliary surrounding conditions	**Required reactions**
Road impact energy	Soft support for road impact
Airflow	Hard constraint for air flow
Water drops	Hard constraints to for rain drops

Step 3: Explosion diagram & optional modules

This step functionally connects the derived actions/reactions to form an explosion diagram as shown in Figure 4.2. The common actions/reactions of both basic and auxiliary functions form a basis. The actions/reactions related to each optional application are added around the basis following their functional relations.

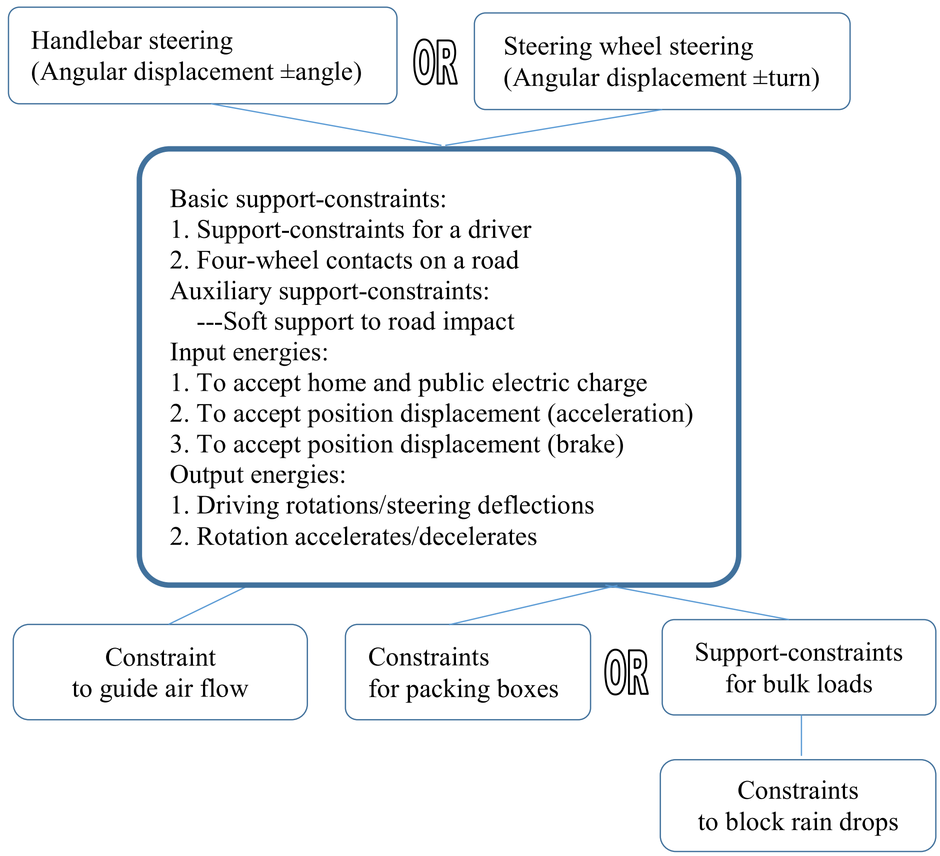


Figure 4.2: Explosion diagram of derived actions/reactions for new MEV

Since each optional application identifies a module, six optional modules can be identified. With a common module, they are listed in Table 4.3. Besides this, modules 2 and 3, modules 4 and 5 are customized modules; modules 6 and 7 are personalized modules.

Table 4.3: Common & optional modules

#	Modules	Type
1	A module for common portion	Common
2	A module for bulk loads	Customized
3	A module for packing boxes	
4	A module for handlebar steering	Customized
5	A module for steering wheel steering	
6	A module for the constraint to guide airflow	Personalized
7	A module for the constraint to block rain drops	Personalized

Step 4: Subsystem building & interface setting

This step builds three sets of subsystems to connect related actions/reactions, and then sets up interfaces to separate the optional modules from the subsystems.

First, there are two customized applications of support-constraints for bulk loads and packing boxes. Combined with the support-constraints for a driver, the soft support-constraints to road impacts, and interface A, two subsystems can be formed considering the spatially arrangements and the shortest force paths as shown in Figure 4.3. Case (A) is for bulk loads; case (B) is for packing boxes.

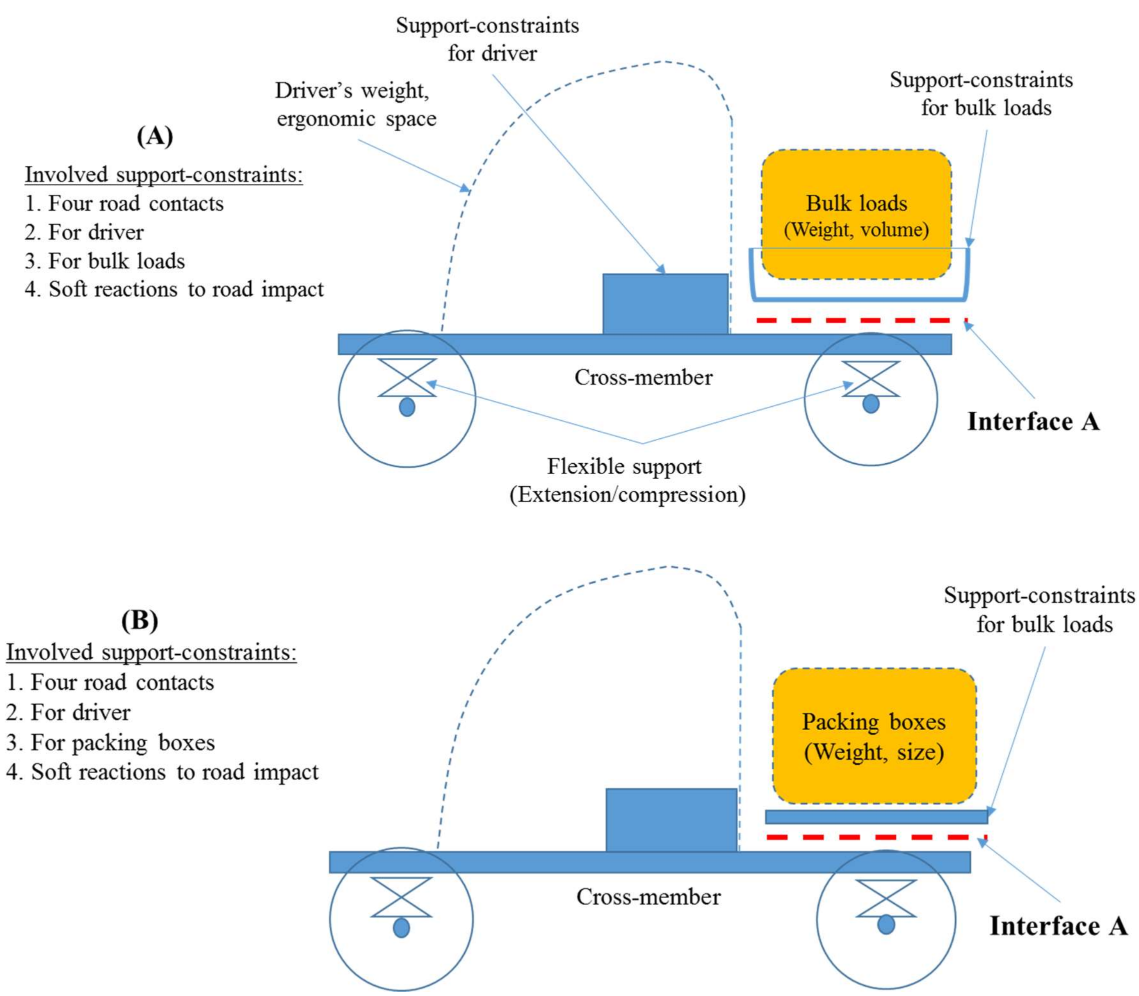


Figure 4.3: The subsystems for different loads

Because they are customized options, they can share a common portion by properly setting an interface. Under this consideration, interface A is set as shown in Figure 4.3 to separate modules 2 and 3 from the subsystems, where the interface interaction is the connection/disconnection of a force path.

The constraints for airflow and rain drops are two personalized options. Based on the arrangement in Figure 4.3 and considering their functional relations, they are arranged as shown in Figure 4.4. Here, a vertical structure is added to support the constraint guiding airflow. Interfaces B, C and D are set as shown in Figure 4.4 to separate modules 6 and 7, where the interface interactions are the connection/disconnection of force paths.

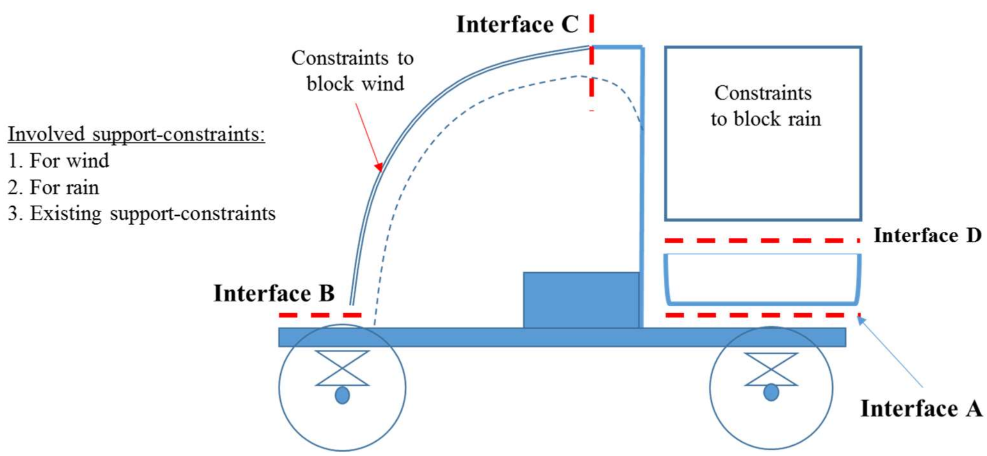


Figure 4.4: The subsystem for wind-proof and rain-proof

Second, there are two customized options of steering. Both options should be connected by the shortest motion flows. Following the Ackerman steering principle, the simplest steering mechanism for each of them is shown in Figure 4.5. Because they are customized options, interface E is set as shown in Figure 4.5 to separate modules 4 and 5 from the subsystems, where the interface interaction is the connection/disconnection of a rotation transmission.

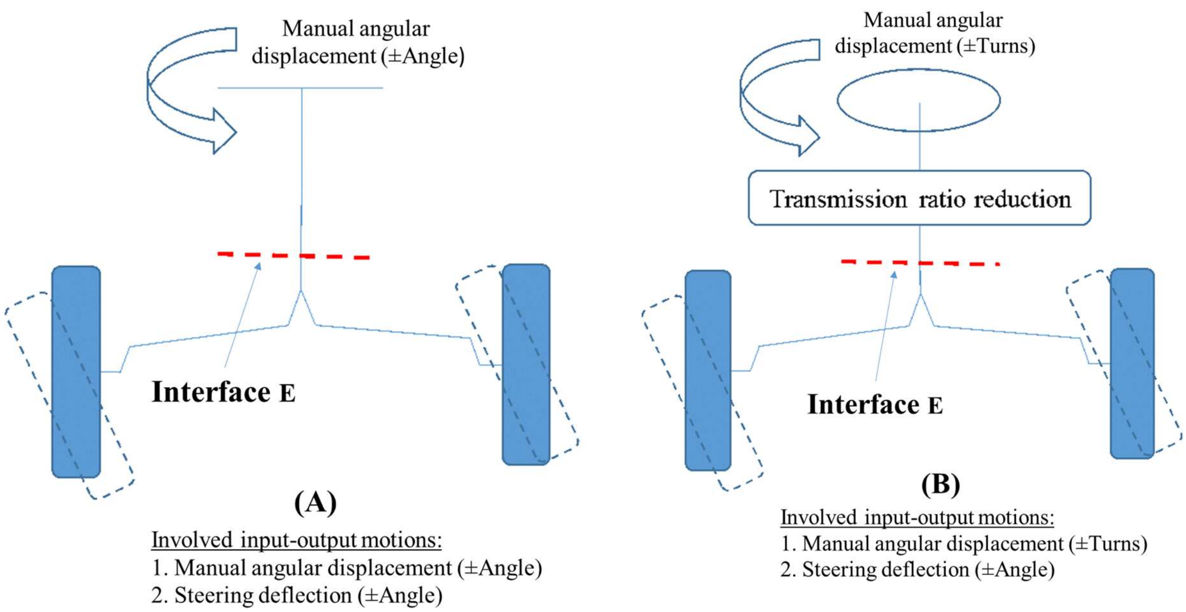


Figure 4.5: The subsystems for handlebar (A) and steering wheel (B)

Third, the driving subsystem is a common subsystem including two driving rotations, and the reactions to accept the electric charge, acceleration and bake controls. There are two concepts that can be adopted. One is a central motor with distributed driving; the other is wheel hub motor driving. Both can meet technical requirements of the MEV. This design selects the former one because its cost is low. This subsystem is developed as shown in Figure 4.6 considering the most efficient energy flows.

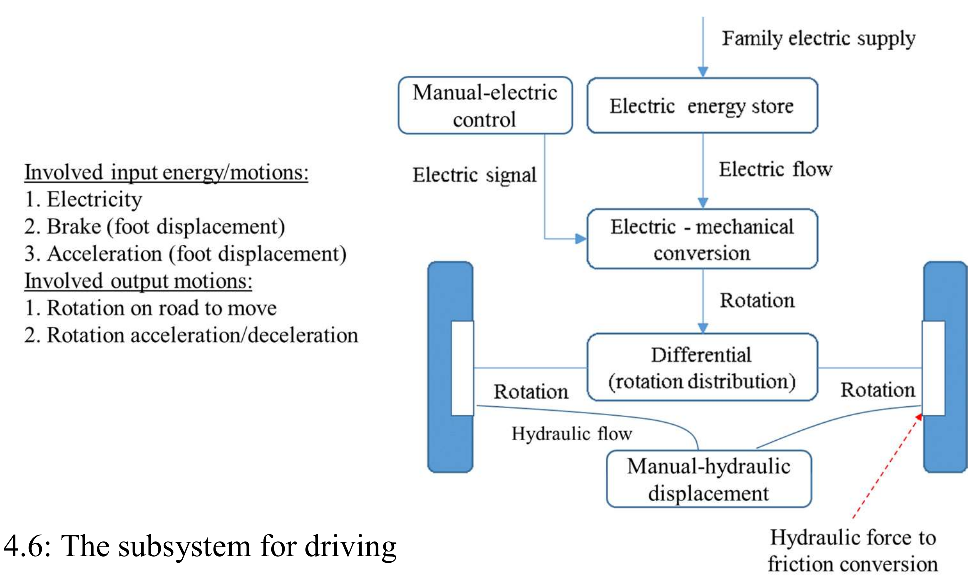
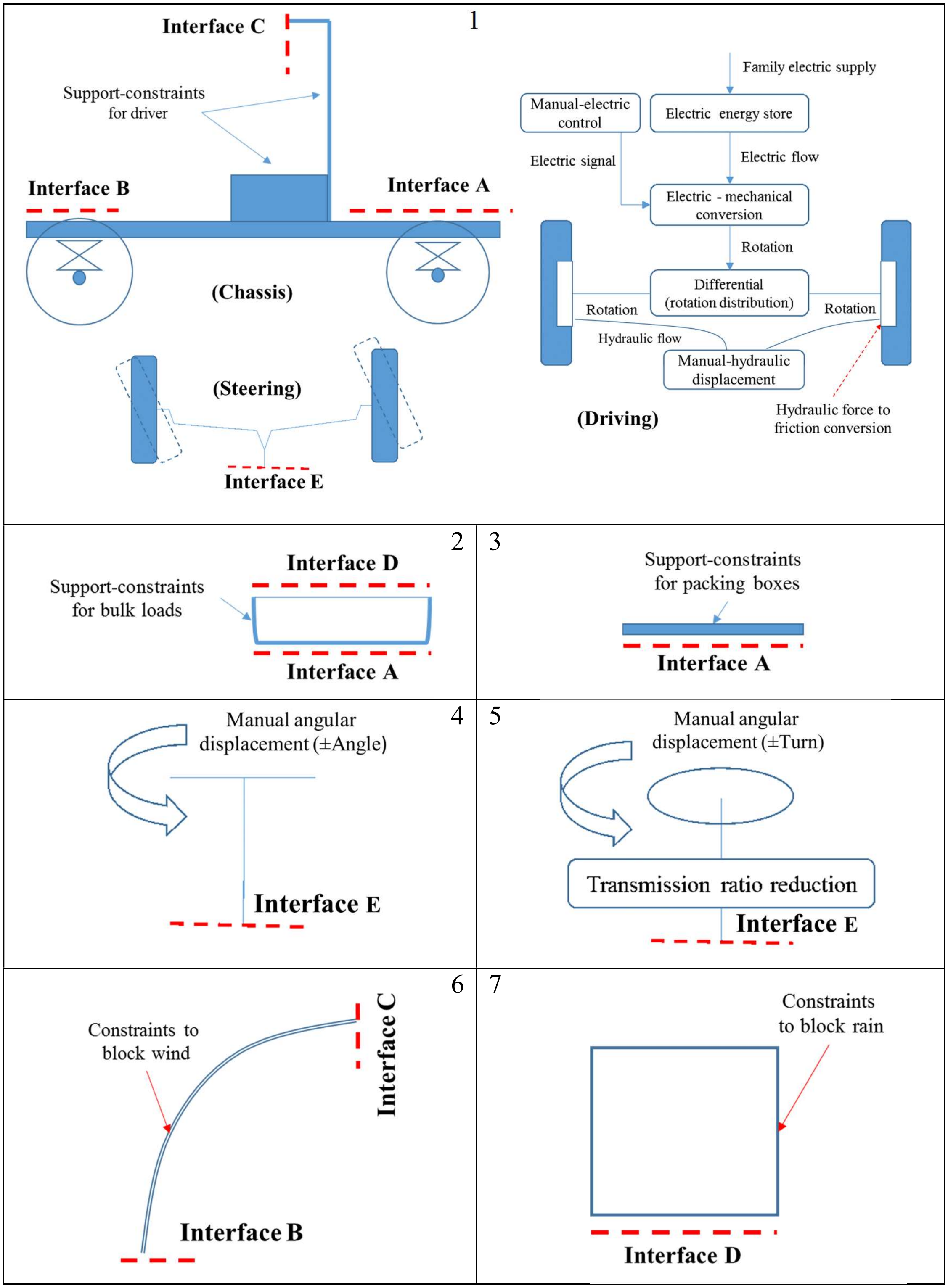


Figure 4.6: The subsystem for driving

Table 4.4: Principal contents of modules



Eventually, this step develops the principal contents of all modules for each module as listed in Table 4.4. The other common portions include the chassis, steering mechanism and driving subsystems can be considered as a platform, because there is not any module to separate them.

Step 5: Overall arranging & interface planning

Since these modules are considered independently, they should be arranged to from an open architecture so that all optional modules can be added/replaced. Under this consideration, the modules are spatially arranged as shown in Figure 4.7. Within the architecture, modules 4 and 5 will be assembled on module 1 at interface E in front of drivers. All optional modules can be added/replaced freely or in certain assembly sequences.

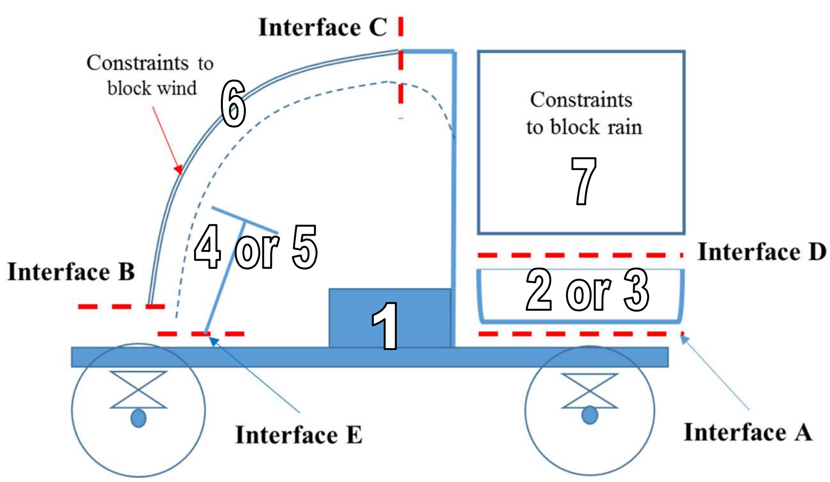


Figure 4.7: Overall arrangement of the MEV

Based on the overall arrangement of modules, since the modules are to be developed, interfaces can be planned as certain mechanical forms so that developed modules can fit the interfaces. Considering the interface alignment, fastening, interaction, and assembly/disassembly, the mechanical forms for each interface are planned as follows:

1. Interface A is in the force path between module 1 and modules 2/3. The preferred form is a set of flat planes with side profile constraints fastened to limit the six-degree freedom. This can also make modules 2/3 a flat bottom to favor loads supporting.
2. Interfaces B and C are in the force paths between modules 1 and 6. Each adopts two fastening points so that total four fastening points to limit the six-degree freedom of module 6.
3. Interface D is in the force path between modules 3 and 7. The preferred form is a set of flat planes with side profile constraints fastened to limit the six-degree freedom.
4. Interface E is in both a force path and a rotation transmission between module 1 and modules 4/5. The preferred form for connection/disconnection of the force path is a flat plane; its six-degree freedom can be limited by the friction force and tension force caused by fasteners. The preferred form for connection/disconnection of the rotation transmission is spline shaft/housing.

The screws and nuts involved in these interfaces are same type and size, so that all assembly/disassembly can be handled by customers using a screw driver and wrench.

4.2 Modules Formation

So far, each module is endued with the principal content of actions/reactions, interfaces, space constraints, and inside energy flows or force paths. Since module 1 is the most complex portion of the MEV, this section will use it to explain the formation of a module following the procedure introduced in Section 3 from step 6 to step 7.

Step 6: Mechanical elements transformation

As shown in Table 4.7, module 1 has the distributed subsystems of chassis, steering, and driving. Each subsystem should be transformed into mechanical elements along energy flows and force paths. The transformation can be processed following the transformation process introduced in Section 3.2.2.

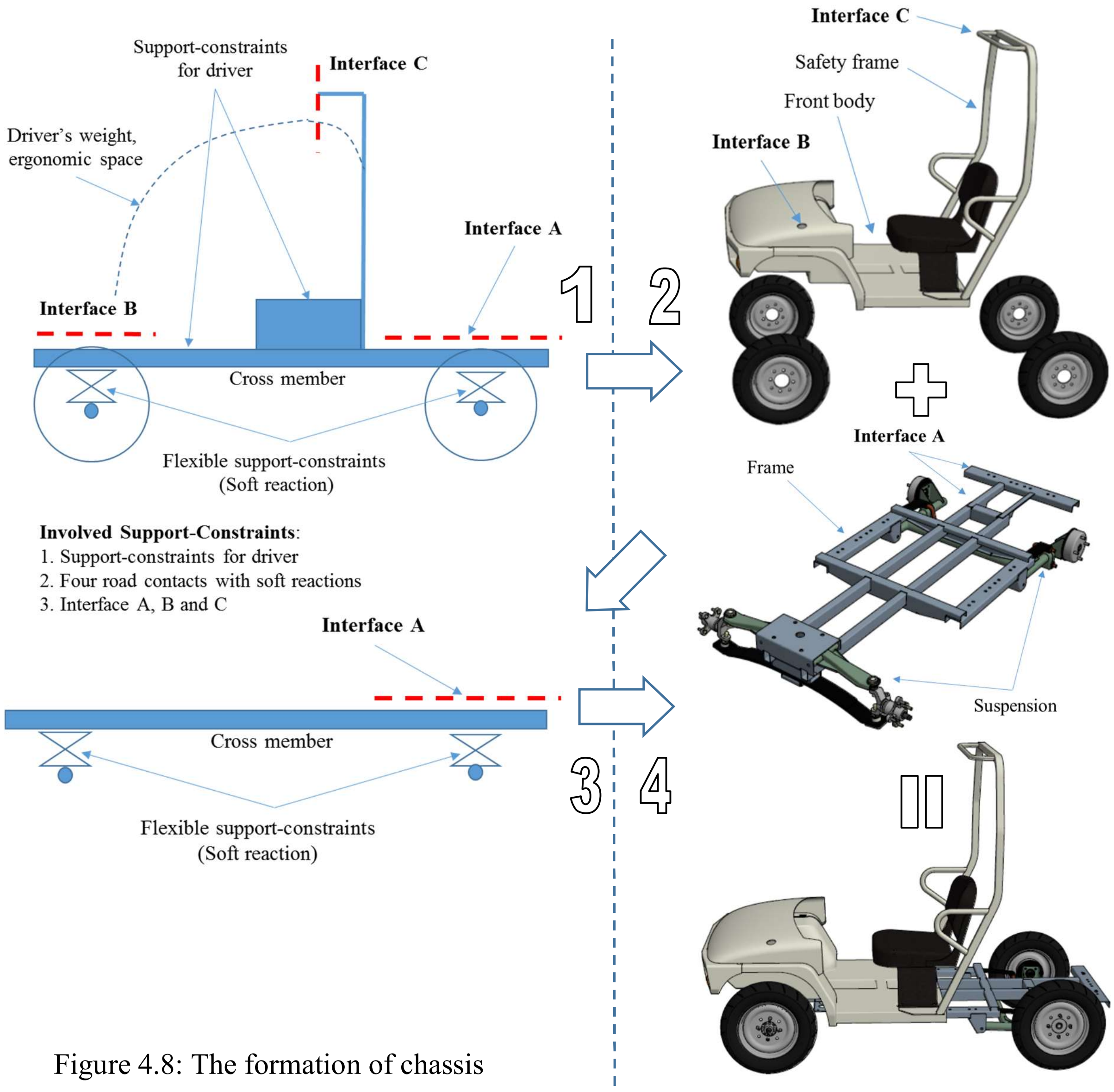


Figure 4.8: The formation of chassis

First, the chassis subsystem is a force-path subsystem. Its transformation can be processed as illustrated in Figure 4.8 following the transformation process shown in Figure 3.6 with following steps:

1. The chassis subsystem is assigned in the principal domain.
2. This step develops the front body, seat and the safety frame to provide support-constraints for a driver, develops interfaces B and C as planned in Step 5, and develops four physical wheel models for four road contacts.
3. These mechanical elements leave the cross-member with interface A, and soft support-constraints as un-solved sections within the subsystem.
4. These un-solved sections should be designed under the constraints including force paths, profile and interfaces. Except these, materials, manufacture capability and cost also affect the design solution. By comparing different classic automotive structures technically and costly, this research develops a chassis frame with “swing arm & leaf spring” suspensions for the un-solved sections in Step3. It supports the front body and form interface A as planned in Step 5.

Second, the steering subsystem is an energy-flow subsystem. Its transformation can be processed as illustrated in Figure 4.9 following the transformation process shown in Figure 3.5 with following steps:

1. The steering subsystem is assigned in the principal domain.
2. This step develops a spline steering shaft for interface E as planned in Step 5 to accept the input rotation, and uses wheel deflections for steering. Meanwhile the intermediate mechanical elements include ball joints and spindles can be selected because they have been developed by professional suppliers.

3. These mechanical elements leave two motion linkages and a rotation distribution as three un-solved sections within the subsystem.
4. Three un-solved sections can be developed under the requirements for the motion linkage and rotation distribution. As an only solution, the tie rods and a central steering arm are developed to form Ackerman steering geometry.

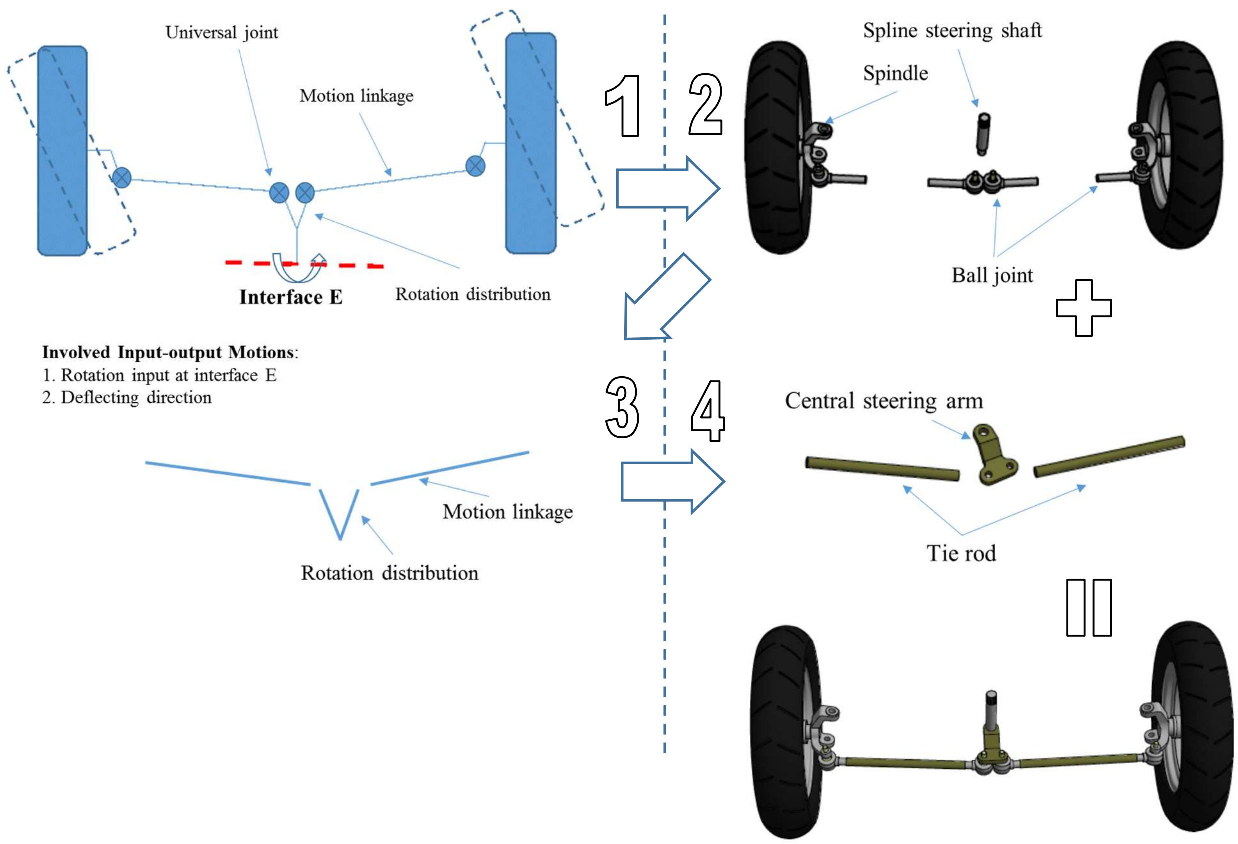


Figure 4.9: The formation of steering subsystem

Third, the driving subsystem is an energy-flow subsystem. Its transformation can be processed as illustrated in Figure 4.10 following the transformation process shown in Figure 3.5 with following steps:

1. The driving subsystem is assigned in the principal domain.

2. This step develops batteries to accept the electric charge, a speed controller for foot acceleration, and a brake panel unit for foot brake; and uses two wheels to drive/brake. An electric motor/differential unit is also developed to implement electric-motion conversion and motion distribution because it is more critical.
3. These mechanical elements leave two rotation transmissions as two un-solved sections within the subsystem.
4. As an only solution, two driving shafts are developed for the un-solved sections in Step 3.

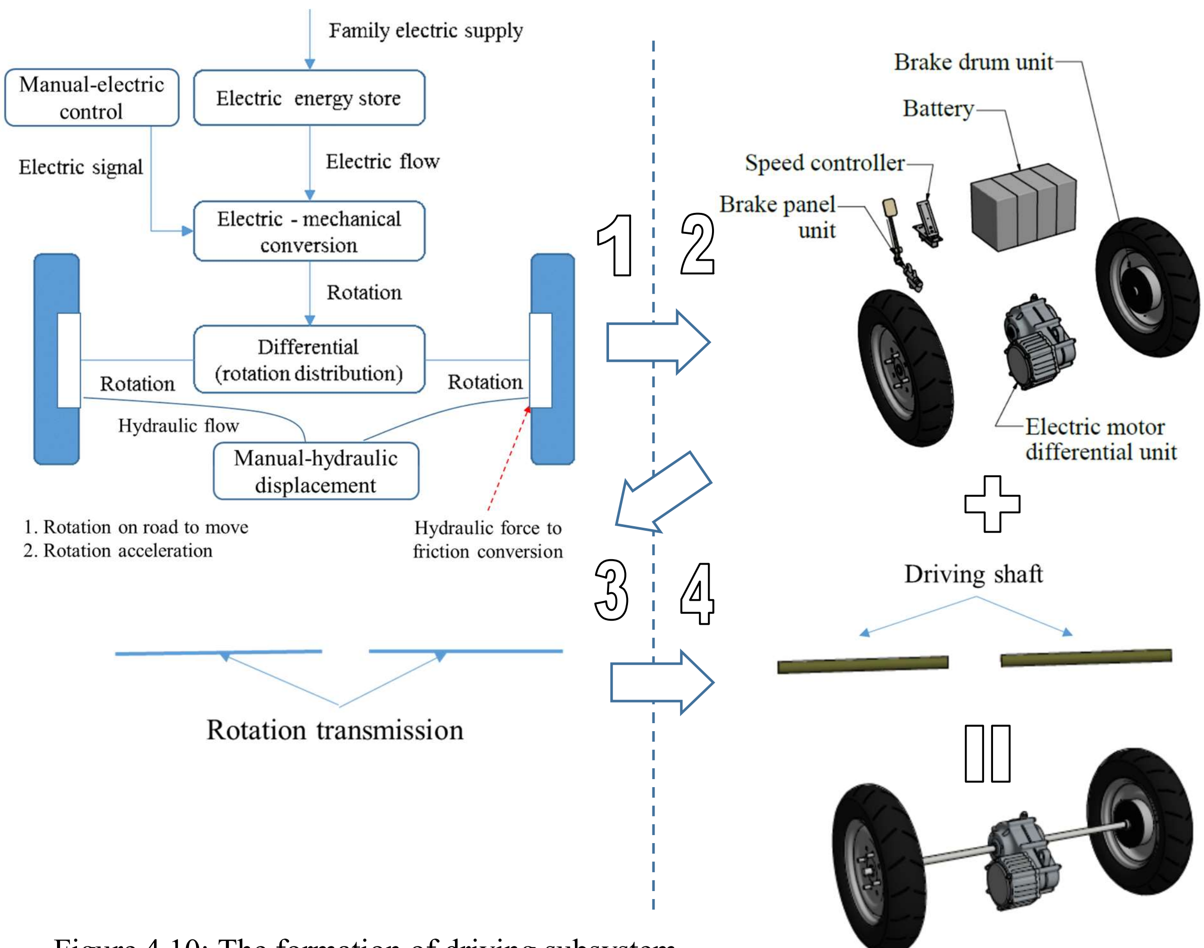


Figure 4.10: The formation of driving subsystem

Step 7: Subsystems combination & mechanical elements integration

This step combines the subsystems into a system (the principal model) in the principal domain and integrates their mechanical elements into a complete module (the physical model) in the physical domains. When combining them together, the chassis should provide support-constraints for steering and driving subsystems and their operations should not disturb each other.

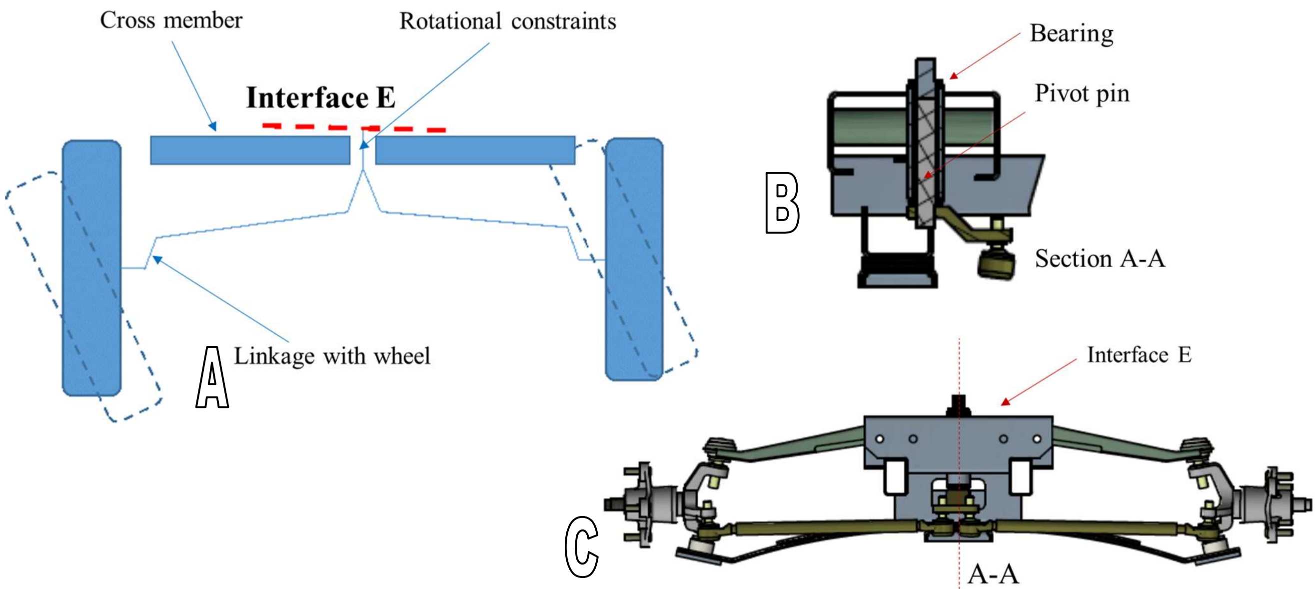


Figure 4.11: Chassis with steering subsystem

Under this consideration, the combination of the steering subsystem with the chassis is shown as Figure 4.11. In the principal domain, the chassis provides a rotational constraint to combine with the steering subsystem and form interface E (Figure 11A). In the physical domain, the rotational constraints are implemented by the steering shaft and bearings (Figure 11B&C); interface E is developed as a bracket of the sheet metal with steering shaft as planned in Step 5. Except this, two subsystems should be combined without the interferences as required.

The combination of the driving subsystem with the chassis is shown as Figure 4.12. In the principal domain, the cross member of chassis provides mounting constraints for the electric motor/differential unit so that interface A has a low height. However, this will cause a transmission confliction between the fixed electric motor/differential unit and two vibrating wheels. For this reason, the straight rotation transmissions are adjusted as two-universal-joint transmissions (Figure 4.12A). In the physical domain, the mounting constraints are implemented by two mounting brackets; the two-universal-joint transmissions are implemented by two driving shafts with universal joints (Figure 12B&C). By these means, the electric motor/differential unit can be fixed on the chassis to transmit power to the wheels.

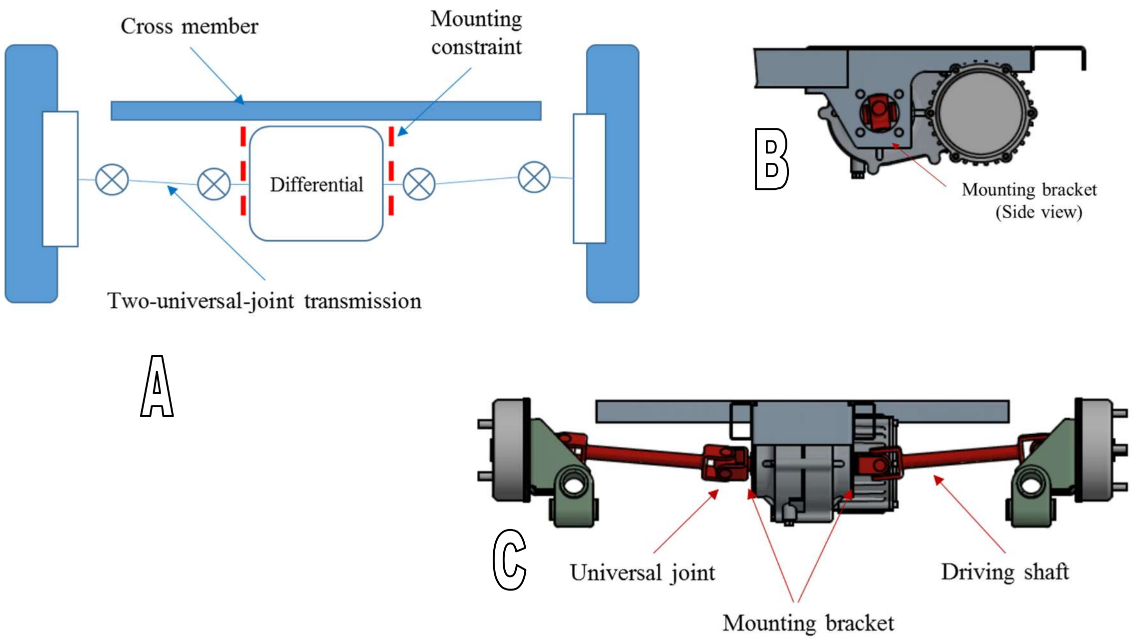
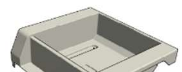
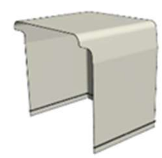


Figure 4.12: Chassis with driving subsystem

Finally, the module 1 is formed as a platform. Since other modules are much simpler, their formations are not introduced here. Seven formed modules with their name are listed in Table 4.5 to form 10 different combinations.

Table 4.5: MEV modules and different combinations

Adaptable products		**Modules**	
 A	 F	 1. Platform	 5. Steering wheel
 B	G 	 2. Rear body (Bulk loads)	 6. Windshield
 C	 H	 3. Rear body (Packing boxes)	 7. Roof
 D	 J	 4. Handlebar	
 E	 K		

Chapter 5

Product Adaptability Evaluation

The product adaptability of an adaptable product mainly reflects in two aspects. One is the various applications supported by the variation of a product; the other is how easy to implement the applications by adding/replacing modules on the product. Both are essentially limited by the space allowance and interface fitting of optional modules. For this reason, criteria including the architecture openness (AO) and interface commonality (IC) are proposed to evaluate the product adaptability.

AO measures the spatial allowance of a product to accept an optional module. Possibilities to meet this requirement are classified as follows:

1. A product has enough room/space to add/replace a module without any obstacle; customers can handle module adding/replacing by themselves.
2. A product has a room/space for a module, but module adding/replacing will cause certain disassembly of the product; customers can still handle module adding/replacing by themselves.

3. There is not a room/space for a module; or a product even has a room/space for a module, customers cannot handle module adding/replacing by themselves.

Three values are assigned for these levels of the architecture openness in Table 5.1.

Table 5.1: Architecture openness

Level	Architecture openness	AO
1	A product has enough room/space to add/replace a module without any obstacle; customers can handle module adding/replacing by themselves.	2
2	A product has a room/space for a module, but module adding/replacing will cause certain disassembly of the product; customers can handle module adding/replacing by themselves.	1
3	There is not a room/space for a module, or a product even has a room/space for a module, customers cannot handle module adding/replacing by themselves.	0

Table 5.2: Interface commonality

Level	Interface commonality	IC
1	An interface is the static connection/disconnection with a flat plane or stripe plane, or the standardized professional connection, such as hydraulic hoses and electric insert.	2
2	An interface is a specialized connection/disconnection developed by manufacturers, or requires an connecting device such as a connector to connect two modules.	1
3	There is no means to connect two modules	0

IC measures the commonality of an interface, including geometric shapes and interactions. As mentioned in Section 3.2.2, simple and common interfaces are preferred because they have less constraints to provide adaptability. For this reason, possibilities to meet this requirement are classified as follows:

1. An interface is the static connection/disconnection with a flat plane or stripe plane, or the standardized professional connection, such as hydraulic hoses and electric inserts.

2. An interface is a specialized connection/disconnection developed by manufacturers, or requires an connecting device such as a connector to connect two modules.
3. There is no means to connect two modules.

Three values are assigned for above interface conditions in Table 5.2.

Tables 5.1 and 5.2 list the typical situations. Adaptability Efficacy (AE) of adaptable products is then defined based on the architecture openness (AO) and interface commonality (IC) as follows:

$$AE = \sum (AO + IC) \qquad (1)$$

The AE improvement can be obtained from Eq. (2).

$$AE_{Improvement} = (AE_{Improved} - AE_{Initial}) / AIE_{Initial} \times 100\% \qquad (2)$$

based on the basic model of an adaptable product.

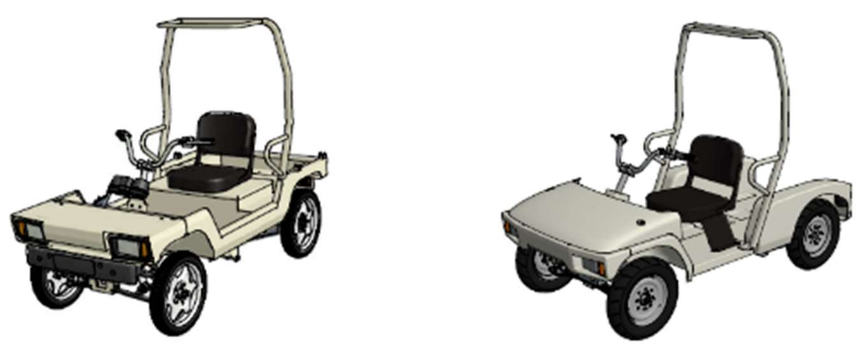


Figure 5.1: The basic models of previous (left) and new (right) MEV

Next, the previous MEV model introduced as the beginning of Chapter 4 and the MEV model developed in Chapter 4 can be evaluated by the proposed evaluation criteria. To have a common comparison basis, the AE will be evaluated based on their basic models as shown in Figure 5.1. The previous MEV model only allows options to add a windshield and a roof in sequence; it does not allow steering wheel options and rear-body options. From Tables 5.1 and 5.2, the values of AO and IC are assigned to each option in Table 5.3. Then, the AE for the previous MEV can be calculated by using Eq. (1).

$$AE = (1 + 1) + (2 + 2) = 6$$

The new MEV can form 10 different combinations. The product adaptabilities can be implemented at four places listed in Table 5.4. From Tables 5.1 and 5.2, the values of AO and IC are assigned to these adaptabilities. Using Eq. (1), AE can be calculated as follow.

$$AE = (1 + 1) + (2 + 2) + (2 + 1) + (2 + 2) = 13$$

Using Eq. (2), AE improvement can be calculated as follow.

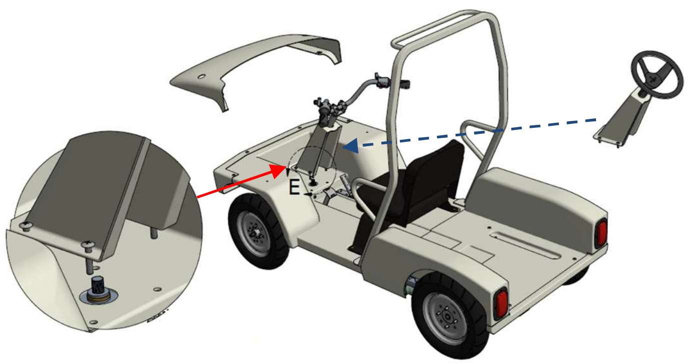
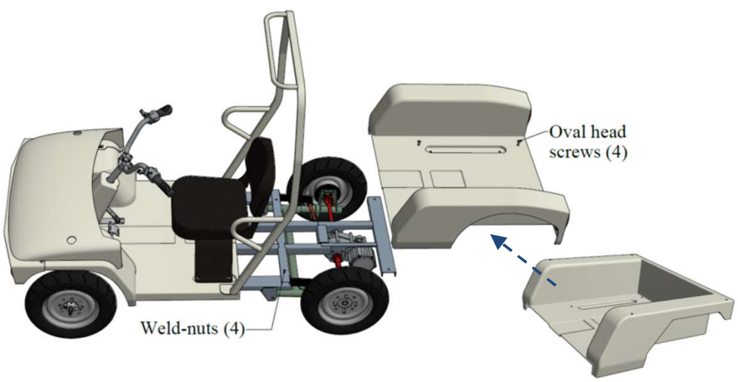
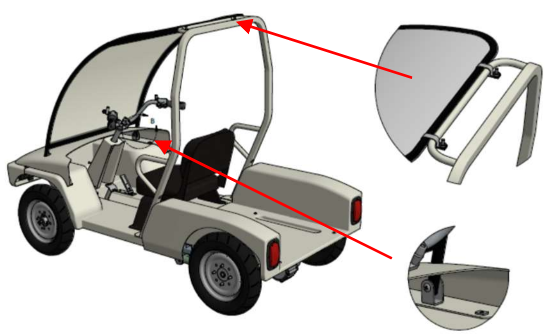
$$AE_{\text{Improvement}} = (13 - 6) / 6 \times 100\% = 117\%$$

Therefore, the design of new MEV has been drastically improved its product adaptability.

Table 5.3: AO and IC of previous MEV

Adaptability/ interfaces	**AO/IC**
	Personalized adaptability SO = 1; A windshield can be added after removing hood; Interface IC = 1; Two mounting brackets/screw-nuts; Two connect clamps/screw-nuts.
	Personalized adaptability SO = 2; E-car has enough space to add a roof; Interface D IC = 2; Two strip planes with four screw-nuts.

Table 5.4: AO and IC of new MEV

Adaptability/interface	AO/IC
	Customized adaptability AO = 1; Two steering modules can be re-placed after removing hood. Interface E IC = 1; A flat plane with four screw-nuts and a spline shaft.
	Customized adaptability SO = 2; E-car has enough space to replace two rear-bodies. Interface A IC = 2; A set of strip planes with four screw-nuts.
	Personalized adaptability SO = 2; E-car has enough space to add a windshield. Interface B and C IC = 1; Two mounting brackets/screw-nuts; Two connect clamps/screw-nuts.
	Personalized adaptability SO = 2; E-car has enough space to add a roof; Interface D IC = 2; Two strip planes with four screw-nuts.

Chapter 6

Conclusions and Future Research

This chapter summarizes conclusions and contributions of this thesis, and gives suggestions for the future research.

This thesis mainly proposes a design method to develop adaptable products. The method starts from customer requirements, and then develops the principal content of actions/reactions, inside energy flows or force paths, space, and interfaces constraints for each module by deriving hierarchical actions/reactions, identifying optional modules, and forming an open architecture, so that each module can be physically formed through a dual-domain formation process. Comparing with the axiomatic design-based on modularization, the proposed method can effectively and efficiently develop an adaptable product with the improved product adaptability. This thesis also proposed a new evaluation method of the product adaptability.

The contributions of this thesis are as follows:

1. Mechanical design is processed in a principal domain and physical domain. The principal domain considers the combination of the energy/force actions to form a principal model; the physical domain considers the combination of the mechanical

elements to form a physical model. The mechanical design implements the transformation from the principal domain to the physical domain by a dual-domain transformation process.

2. Customer requirements are met by hierarchical actions/reactions that can form an explosion diagram to identify optional modules. The actions/reactions can be connected by energy flows and force paths to form subsystems, so that the optional modules can be separated by setting interfaces where the energy flows and force paths are separable and have the minimum interactions.
3. Product adaptability is implemented considering the spatial allowance and interface fitting of optional modules by forming an open architecture.

Although this thesis proposes a method for AD, some areas related to this method are still not sufficient in applications. One area is the derivation of required actions/reactions from customer requirements. Different actions/reactions will result in different design solutions, the creation and comparison of design solutions are critical for an optimized solution. This thesis does not go deep in this area. Another area is the formation of each module. To form a physical module, all mechanical elements should be formed with desired interfaces and profiles. When integrating these mechanical elements, the limitation of materials, manufacture capability, and even the principles of subsystems can cause conflicts such as the interference and un-matching. Thus, the geometric profile based optimization becomes an important consideration to form each module. Therefore, these two areas are proposed as the research direction in the future work so that the proposed method can be effectively applied.

References

Beek, J., Erden S., & Tomiyama, T. (2010). Modular design of mechatronic systems with function modeling. Elsevier Mechatronics, 20, 850-863

Cascini, G., Frate, L., Gualtiero, Fantoni G., & Montagna F. (2011). Beyond the Design Perspective of Gero's FBS Framework. Gero, J. S., Editor, Design computing and cognition ’10. Springer, 77-96

Chen, K., & Liu, R. (2005). Interface strategies in modular product innovation. Technovation. 25, 771-782

Cheng, Q., Zhang G., Gu, P., & Shao, X. (2012). A product Module Identification Approach Based on Axiomatic Design and Design Structure Matrix. Concurrent Engineering. Research and Applications

Cheng, Q., Zhang, G., Liu, Z., Gu, P., & Cai, L. (2011). A structure-based approach to evaluation product adaptability in adaptable design. Journal of Mechanical Science and technology, 25(5), 1081-1094

Clark, B., & Fujimoto, T. (1991). The Power of Product Integrity. Harvard Business Review, Nov-Dec.

Dahmus, B., Gonzalez-Zugasti, P. & Otto, N., (2001). Modular Product Architecture. Design Studies, Vol 22 No. 5 September, 409-424

Eager, A., Elsam, K., Gupta, R., & Velinder, M. (2010). Modular Design Playbook "Guidelines for Assessing the Benefits and Risks of Modular Design". Research & Technology Executive Council.

Eggen, O. (2003). Modular Product Development - A review of modularization objectives as well as techniques for identifying modular product architectures presented in a unified model. Norway University of Science and Technology.

Fixson, K., & Park, J. (2008). The Power of Integrality: Linkages between Product Architecture Innovation and Industry Structure. Research Policy, 37, 1296-1316

Fletcher, D. (2007). Adaptable Design for Quantification. PHD thesis, University of Calgary, Department of Mechanical and Manufacturing Engineering.

Foss, K. (1998). Modular Product Design: Modular Product Design - Creating "Technologically Separable Interfaces". Department of Industrial Economics and Strategy, Copenhagen Business School.

Gero, J. S., & Kannengiesser, U. (2004). The situated function–behaviour– structure framework. Design Studies, 25, 373–39

Gu, P. (2003). Mechanical Bus for Modular Product Design. Annals of CIRP

Gu, P. (2004). Adaptable Design with Flexible Interface System. Society for Design Process Science, Sept, Vol. 8, No. 3 pp. 61-74

Gu, P., Xue, D., & Nee, A Y C. (2009) Adaptable Design: concepts, methods, and applications. Journal of engineering manufacture, November 1, vol. 223 no. 11 1367-1387

Hashemian, M. (2005). Design for Adaptability. PhD thesis, the University of Saskatchewan, Department of Mechanical and Manufacturing Engineering

Helmer, R., Yassine, A. & Meier, C. (2010). Systematic module and interface definition using component design structure matrix. Journal of Engineering Design. Vol. 21, No. 6, December 2010, 647-675

Hölttä, K., Suh S., & Weck O. (2005). Trade-off between Modularity and Performance for Engineering Systems and Products. International conference on engineering design, ICED 05 Melbourne, August 15-18

Hölttä, K., & Otto, N. (2005). Incorporating Design Effort Complexity Measures in Product Architectural Design and Assessment. Elsevier Design Studies, 26, 463-485

Hu, C., Peng Q., & Gu, P. (2014). Adaptable Interface Design for Open-architecture Products. Computer-Aided Design and Applications, Volume 11, Issue 2

Huang, C. (2000). Overview of Modular Product Development. Proc. Natl. Sci. Counc. ROC (A) Vol.24, No. 3, pp. 149-165

Janthong, N., Brissaud, D., & Butdee, S. (2009). Adaptability Design to Meet Dynamic Customer's Needs. IEEE international Conference on Industrial Engineering and Engineering Management (IEEM09), hal-00413946, version 1-7 Sep

Levandowski, C., Jiao J. & Johannesson H. (2015). A two-stage model of adaptable product platform for engineering-to-order configuration design. Journal of Engineering Design

Li, Y. (2007). Design for Product Adaptability. Master thesis, University of Calgary, Department of Mechanical and Manufacturing Engineering

Miller, D., & Eldard, P. (1998). Defining Modules, Modularity and Modularization. Design for integration in manufacturing, proceedings of the 13th IPS research seminar, Fuglsoe, ISBN 87-89867-60-2

Otto, N., & Wood, L. (1998). Product Evolution: A reverse Engineering and Redesign Methodology. Research in Engineering Design 10: 226-243

Pahl, G., Beitz, W. (2007). Engineering Design: A Systematic Approach. Springer - London

Peng, Q., Liu Y., & Gu P. (2014). Improvement of product adaptability by efficient module interactions. IDETC/CIE, Volume 4

Peng, Q., Liu Y., Gu, P., & Fan, Z. (2013). Development of an open-architecture electric vehicle using adaptable design. Azevedo, A., editor, Advances in Sustainable and Competitive Manufacturing Systems, 79-90

Rahmani, K., & Thomson, V. (2012). Ontology based interface design and control methodology for collaborative product development. Computer-Aided Design 44, 432-444

Simpson, W., Jiao, J., & Siddique, Z. (2013). Advances in Product Family and Product Platform Design: Methods & Applications. Springer

Stone, R., Wood, K., & Crawford, R. (2001). A Heuristic method to identify modules from a functional description of a product. Design Studies 21, 5-31

Suh, N. P. (2001). Axiomatic Design Advances and Applications. Oxford University Press

Ulrich, K. (1995). The role of product architecture in the manufacture firm. Research Policy 24, 419-440

Vermaas, P. E., & Dorst, K. (2007). On the conceptual frame work of John Gero’s FBS-model and the prescriptive aims of design methodology. Elsevier, Design Studies 28, 133-157

Wang, C., Liu, C-Y., & Liu, A. (2015). Managing Functional Coupling Sequences to Reduce Design Complexity During Concept Improvements, ASME, DETC-46956

Yin, Y., Kaku, I., & Liu, C. (2012). Product architecture product development process system integrator and product global performance. Product Planning & control, 1-17

Zhang, J. (2014). Adaptable Design of Mechanical Product with Robust Performance. PHD thesis, University of Calgary, Department of Mechanical and Manufacturing Engineering

Zhang, J., Xue, D., & Gu, P. (2015). Adaptable design of open architecture products with robust performance. Journal of Engineering Design, Vol. 26, Nos. 1–3, 1–23